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EFFECT OF OVERHEATING ON CREEP-RUPTURE

PROPERTIES OF M-252 ALLOY

By John P. Rowe and J. W. Freeman

University of Michigan



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SUMMARY

A study was carried out of the influence of periodic overheats of 2-minute duration to temperatures of 1,650°, 1,800°, 1,900°, and 2,000° F on the creep-rupture properties of M-252 alloy at 1,500° F. The conditions of the experiments had been selected to provide basic information applicable to estimation of the effects of overheating on creep-rupture performance of gas-turbine parts. The overheats were conducted both with the stress removed during overheating and with stress present.

Overheating M-252 alloy to 1,900° or 2,000° F in the absence of stress did not reduce creep-rupture life at 1,500° F but actually increased it. For overheating to these temperatures to reduce rupture life, a stress sufficient to use up a significant amount of the rupture life must be present during the overheats. Overheating to 1,650° and 1,800° F with the stress removed during the overheats reduced rupture life at 1,500° F although this was not found to be true in the presence of stress.

The increase in rupture life of M-252 alloy from overheating was considered to be the result of structural changes induced by the higher temperatures. This behavior was in contrast with the results of previous studies of S-816 and HS-31 alloys where the high-temperature effect always reduced rupture life. Summing the effects of temperature and the percentage of rupture life used up during the overheats when stress was present gave close approximations of the actual rupture times in most cases for tests in which stress was present during the overheats. While the stress damage can be estimated from rupture data, there does not appear to be any way to estimate the temperature effects other than by conducting tests.

Overheating prior to testing does not give the same effect as the same accumulated time from periodic brief overheats during a test. In M-252 alloy such prior heating to any of the temperatures considered reduced rupture strength at 1,500° F.

In M-252 alloy a few periodic overheats had no significant effect on creep-rupture life at 1,500° F other than to accelerate slightly the

accumulation of small amounts of total deformation. This means that for a few overheats to affect creep-rupture life of turbine parts significantly a stress sufficient to use up a significant amount of creep-rupture life must be present during the overheats. In the absence of such stresses, damage from a few overheats must arise from some other factor such as thermal shock or accelerated corrosion. This is the same as the general previous findings for S-816 and HS-31 alloys, except that a significant amount of damage could be introduced into these alloys by one overheat to 2,000° F of 2-minute duration. For overheating alone to reduce turbine life significantly repeated or prolonged overheating must occur, unless the stress is high or temperatures of 2,000° F are attained with S-816- and HS-31-alloy parts.

There are a number of limitations to the results and conclusions which should be considered. The general trends of the effects, however, are believed to be correct. In particular, care should be exercised in concluding without further proof that all alloys strengthened by the alloying of titanium and aluminum will react in the same way as M-252 alloy. It is also felt that the mechanism of the effects should be better understood before too much generalization will be validated. The experimental conditions were quite limited, particularly for tests under stress during overheating. Also, more information is needed regarding the influence of such metallurgical variables as heat treatment and heat-to-heat differences.

INTRODUCTION

An investigation was carried out to evaluate the effects of brief overheats to temperatures of 1,650°, 1,800°, 1,900°, and 2,000° F on the creep-rupture properties at 1,500° F of M-252 alloy. The objective of the investigation was to obtain basic information on the changes in creep-rupture properties of the alloy if it is exposed to overheating of the type which might occur during jet-engine operation. Two previous reports on similar investigations for S-816 and HS-31 alloys have been published (refs. 1 and 2).

The effects of overheating were evaluated in terms of the changes in creep-rupture characteristics at 1,500° F under stresses within the range of rupture strengths of the M-252 alloy for about 80 to 1,000 hours. The possible effect of overheating was considered to include internal structural changes induced by exposure to the higher temperatures and loss in life by creep if stress was present during the overheats. The effect of temperature was evaluated by starting tests at 1,500° F and then periodically overheating with the stress removed during the over-heat periods. Creep damage during the overheats was evaluated by leaving stress on the specimens during the overheats. The experiments involving

overheating in the presence of stress were designed to check the feasibility of computing damage by an "addibility-of-life-fraction" rule. This rule postulates that the rupture life at $1,500^{\circ}\text{F}$ would be reduced the same percentage as the percent of rupture life at the overheat temperature represented by the total time under stress.

Overheat periods were predominately 2 minutes in duration and were applied cyclically at approximately 5- or 12-hour intervals, depending on the normal rupture time under the stress being used at $1,500^{\circ}\text{F}$. These schedules were adopted to provide the most useful general results after consideration by the Subcommittee on Power-Plant Materials of the National Advisory Committee for Aeronautics of the variable conditions under which overheating could occur in jet-engine service. It should be clearly recognized that the intent was to develop general principles and not to evaluate the specific conditions of overheating which can occur in a specific jet engine. The investigation was also limited to the effects of overheating on creep-rupture properties. The overheat conditions did not include the effects of differential restrained expansion (thermal shock) or the possible effects on such other properties as fatigue strength and corrosion resistance.

Considerable difficulty was encountered in obtaining M-252 stock for the investigation with sufficiently high rupture strength at $1,500^{\circ}\text{F}$ to be acceptable as typical of the alloy. Several heats were checked for normal rupture-test properties at $1,500^{\circ}\text{F}$ and a few overheat tests conducted before approved material for the bulk of the investigation was obtained.

The investigation was carried out by the Engineering Research Institute of the University of Michigan under the sponsorship and with the financial assistance of the NACA. It was part of a general research investigation studying metallurgical factors involved in the use of heat-resistant alloys in aircraft propulsion systems.

PROCEDURE

Overheating can be expected to have two main effects on creep-rupture life at some lower nominal temperature:

- (1) A change in subsequent creep-rupture life because of the exposure to higher temperature changing the internal structure of the metal. This is designated "temperature effect" in subsequent discussions.
- (2) Accelerated creep when the temperature is increased in the presence of stress, subsequently referred to as "stress damage."

In addition, the cyclic removal and reapplication of the stress during the overheat experiments in the absence of stress could alter the creep-rupture characteristics. The influence of overheats could also be expected to vary depending on the stress level and rupture time at the nominal test temperature. In consideration of these factors the following test program was established.

Evaluation of Test Material

The test material was evaluated as follows:

(1) Bar stock was supplied by members of the NACA Subcommittee on Power-Plant Materials for the experimental program. This stock was first checked for creep-rupture strength at 1,500° F to be sure that its properties were typical of the alloy. Five heats were checked before material with sufficiently high strength to be typical was obtained.

Considerable concern over the level of strength developed when stock with somewhat low rupture strength exhibited an increase in rupture time at 1,500° F as a result of overheating in the absence of stress. It seemed necessary to be sure that this effect was the direct result of overheating and not due to some part of the stock having low initial rupture strength at 1,500° F.

(2) Rupture properties were evaluated at the overheat temperatures as well as at 1,500° F. This was done so that a measure of strength at overheat temperatures would be available for checking the feasibility of computing damage from overheats when stress was present. Various amounts of this was done on low-strength heats, as well as on the normal-strength heat finally selected for the bulk of the investigation, before the necessity of using the high-strength material was recognized.

Determination of Temperature Effect From Overheating in Absence of Stress

The temperature effect was determined by overheating the specimens in the absence of stress as follows:

(1) The basic measurement was the effect on the rupture time at 1,500° F of repeated cyclic overheats to 1,650°, 1,800°, 1,900°, and 2,000° F with the stresses at 1,500° F for most of the work selected to cause rupture in a normal rupture test in 80 or 490 hours. The number of overheats was varied by stopping overheats after various proportions of the total rupture life had been expended.

(2) In addition, the effect of cycling the load at 1,500° F was also studied.

Overheating in Presence of Stress to Establish Stress Damage

Stress damage caused by overheating the specimens in the presence of stress was determined as follows:

(1) Consideration of the stress and rupture-time characteristics of the alloy, as presented later, indicates that the stresses at 1,500° F used for the study of the effect of overheating in the absence of stress would be so high as to either use up an unduly large fraction of the available life or actually be above the tensile strength if maintained during the overheats. Thus, only the overheating to 1,650° F and a limited amount at 1,800° F was done under the stresses which were employed at 1,500° F.

(2) For the tests overheated to the higher temperatures considered in this investigation the stresses present during the overheats were changed in order to evaluate the "addibility-of-life-fraction" principle postulated. The stress used at 1,500° F for most of these tests was that causing rupture in 490 hours. The stresses selected for use during the overheat cycles in the presence of stress were determined in the following way:

(a) It was the intent of this part of the program to establish test conditions which would permit the evaluation of the principle of adding rupture-life fractions at the two temperatures used and then to determine the way in which the effects of the overheat temperature itself influenced the results obtained. To accomplish this goal the stress levels were adjusted in such a way as to result in the use of a significant amount of the available life at both 1,500° F and the overheat temperature. It was considered that the loss of about 30 percent of the available life at the overheat temperature would be significant.

(b) Under the stress normally causing rupture in 500 hours at 1,500° F, reducing the rupture life at 1,500° F by 30 percent would, in the absence of any other effect, result in a rupture time of about 350 hours.

(c) Using a schedule of overheating twice a day, there would be 29 overheats in 350 hours, with a total time at the overheat temperature of 58 minutes.

(d) For 58 minutes to be 30 percent of the available life at the overheat temperature, the stress selected for use during the

overheats had to be that causing rupture in 58/0.3 or 193 minutes. In most cases then this was the stress selected for overheating. A few tests were run with the full stress remaining during the overheats to check on the effect of overheating under high stress.

The actual rupture times obtained under these conditions varied depending on the effect of the temperature which was employed for the overheats. Thus, the actual amount of the life which was used up at the overheat temperature varied from the aim amount of 30 percent. At the end of each test, however, calculation could be made of the actual fraction of the normal rupture life at the overheat temperature and stress which was represented by the total time of overheating.

MATERIAL

Five heats of material were supplied for consideration in this program. Three were air-melted heats and the other two had been melted in vacuum. Table I shows the reported chemical composition of all the heats and the source of the material, all of which was supplied gratis in the form of bar stock.

Initially it was found that the standard heat treatment (4 hours at 1,950° F, then air-cooled, plus 15 hours at 1,400° F and air-cooled) produced nonuniform grain size known to cause unpredictably variable rupture properties. To avoid this difficulty and produce more uniform material, the bar stock from all of the heats was hot-rolled to 1/2-inch broken-cornered squares at the University of Michigan. The rolling was done from 1,950° F with one or more reheats depending on the size of the bars as received for all the heats except the Haynes Stellite vacuum-melted heat HT-28. Initially this heat was also rolled at 1,950° F but subsequent work indicated that higher strength was obtained if the rolling was carried out from 2,150° F, and this condition of the material was used for the main body of the overheat experiments.

The properties of all of the heats supplied are compared in a later section.

EXPERIMENTAL TECHNIQUES

Testing Equipment

The creep-rupture testing was carried out in conventional beam-loaded creep-rupture units using specimens with a 0.250-inch diameter and 1-inch

gage length. Each sample was accurately measured before testing. Time-elongation data were taken during the tests by the use of a modified Martens-type optical extensometer with a sensitivity of ± 0.00001 inch. The units were equipped with automatically controlled furnaces for heating specimens. Temperature variations along the gage length were held to $\pm 3^\circ$ F. For all tests the furnaces were turned on and allowed to come to temperature overnight. The specimens were then placed in the hot furnace, brought on temperature, and loaded within a maximum of 4 hours.

For overheat tests, the conventional units were modified to permit resistance heating of the specimens by passing heavy direct current through the sample. A 400-ampere, direct-current generator was used as a power supply. In order to avoid disturbing the specimen during the test, insulated terminal blocks were fastened to the frame of the unit level with the top and bottom of the furnace. From these terminals, short leads were fastened to the top and bottom specimen holders before the test was started. Then, for overheating, it was necessary to attach the power supply leads to only the terminal blocks, completing the circuit to the generator field switch. The top specimen holder was insulated from the frame by means of a Transite insert. The whole circuit was grounded either through the beam or through an attached ground wire. A photograph of a unit is shown as figure 1.

In order to follow the temperature accurately during an overheat, a welding technique (ref. 3) was employed to attach Chromel-Alumel thermocouples to the specimens and an electronic indicating potentiometer. A schematic sketch of this arrangement is shown as figure 2. Temperature measurement was complicated by two factors. In order to follow the rapidly changing temperatures during an overheat cycle and effect accurate control, the thermocouple wires had to be welded to the sample. This was done with a percussion-type welder. The welded attachment maintained the thermocouple bead in contact with the specimen as reduction in cross section occurred by creep during the tests. In welding the thermocouple wires on the specimen, however, any minute error in positioning either wire caused the direct current from the generator to impress an electromotive force on the thermocouple circuit. This electromotive force varied with the magnitude of the placement error and appeared on the temperature indicator as a temperature effect. To avoid this, two Alumel wires were employed, one deliberately placed on either side of the single Chromel wire. By connecting these two Alumel wires to the extremes of a variable resistance, the variable tap could be adjusted so that the two electromotive forces obtained cancelled each other, leaving only the thermal electromotive force impressed on the indicator.

Checks were made of the original calibration and the maintenance of calibration of the thermocouples. The system used gave accurate

temperature measurements as installed. The cyclic overheats did not change the calibration by any more than 1° F at any of the temperatures.

Overheating Procedures

This investigation included three types of overheats: Overheats before testing, overheats in the absence of stress, and overheats in the presence of stress. Each type required a different procedure involving the described equipment.

Overheats before testing.- Overheating before testing was carried out in two ways, depending on the duration and temperature of overheating. The procedures used were as follows:

(1) Tests overheated to $1,600^{\circ}$ F for long time periods were loaded in the creep furnace exactly as for a creep-rupture test. After being brought on temperature at $1,500^{\circ}$ F, the furnace temperature was raised rapidly to $1,600^{\circ}$ F, held for the desired time period, and then cooled to $1,500^{\circ}$ F. The load was then applied and the test run to rupture.

(2) All samples overheated to $1,650^{\circ}$, $1,900^{\circ}$, and $2,000^{\circ}$ F before testing were prepared in the following manner. A thermocouple was attached to each sample. A heat-treating furnace was brought on temperature and held to assure equilibrium. The samples were then placed in the furnace and the time counted from the point at which the temperature indicated by the attached couple reached 10° F below the desired temperature. Following completion of the required time at temperature, the specimens were removed from the furnace and air-cooled. They were then set up and the test run as a standard creep-rupture test.

Overheats in absence of stress.- All overheating done in the absence of stress was of a cyclic nature where the described cycle was repeated a predetermined number of times. For these tests the specimens were prepared with a thermocouple welded at the center as described previously and an additional thermocouple mechanically attached at each end of the reduced section for checks on temperature distribution along the gage length. They were placed in the creep furnace and started exactly as in a normal creep-rupture test at $1,500^{\circ}$ F except that the short power leads were attached to the specimen holders before stressing. Then, after the completion of the desired time period under stress at $1,500^{\circ}$ F before the first overheat, the following procedure was followed in performing an overheat:

(1) The temperature was checked and an elongation reading made. At this time, the power leads from the generator were attached to the unit and the welded thermocouple was connected to the indicating potentiometer.

(2) The load was removed.

(3) After a 60-second time lapse during which the furnace input was cut back and the thermocouple circuit checked, the heating cycle was initiated by applying the maximum generator output of 400 amperes to the specimen. When the desired overheat temperature was attained, the generator output was reduced to a value just sufficient to maintain temperature.

(4) At the end of the established cycle duration, the power supply was cut off and the specimen allowed to cool. No forced cooling was employed other than that supplied by having allowed the furnace temperature to fall below $1,500^{\circ}\text{F}$ when the input was reduced in step (3).

(5) The load was reapplied when the temperature reached $1,510^{\circ}\text{F}$. Because of the asymptotic approach of the specimen temperature to $1,500^{\circ}\text{F}$, this temperature was difficult to establish while the time to reach $1,510^{\circ}\text{F}$ was nearly constant. After reapplication of the load, the furnace was manipulated to bring the temperature to $1,500^{\circ}\text{F}$ as soon as possible.

(6) When temperature equilibrium was reestablished at $1,500^{\circ}\text{F}$, elongation measurements were taken again and the test continued to the next cycle. In plotting the time-elongation data, this reading after reapplication of the load was assumed to be at the same total deformation as the reading taken just prior to removal of the load at the beginning of the cycle.

(7) Typical time-temperature patterns for overheats of 2 minutes to each of the temperatures used are shown in figure 3.

Overheats in the presence of stress.- Overheats in the presence of stress were performed exactly as the ones where stress was absent during overheats except that the load, or part of the load, was left on the specimens. Deformation measurements were made before each cycle and again after equilibrium was reestablished at $1,500^{\circ}\text{F}$ to measure the deformation which occurred during each overheat cycle.

Metallurgical Studies

As an aid in evaluating the cause of the measured effects of overheating, microstructural examination of the test samples was carried out. Longitudinal sections of the fractured samples were cut from the gage length at the fracture. These were mounted and mechanically polished. The polished surface was then etched electrolytically and examined at magnifications of 100 and 1,000 diameters.

RESULTS AND DISCUSSION

The test results definitely show that for M-252 alloy tested at 1,500° F the effect of overheating in the absence of stress depends on the temperature at which overheating is carried out. Overheating from 1,500° F to temperatures up to 1,800° F can result in a reduction of rupture life at 1,500° F, while overheating to temperatures of 1,900° F and 2,000° F can result in a prolongation of rupture life.

When stress was present during an overheat to 1,900° or 2,000° F, the results reflected a combination of the previously determined temperature effects and the loss in rupture life resulting from the presence of the stress during the overheat. For some conditions, therefore, the net effect was an increase in life. When overheating was carried out in the presence of stress to 1,650° or 1,800° F, the test results were longer than would be estimated from the anticipated effects of temperature and stress.

Normal Rupture Properties of Experimental Materials

Rupture tests were conducted at 1,500° F on the test material for the following purposes:

- (1) To establish curves of stress against rupture time so that proper stresses could be selected for the overheat tests
- (2) To establish the normal rupture-test performance so that the effects of overheating could be evaluated

In addition, tests were conducted at overheat temperatures so that the effect of stress during overheats could be evaluated.

When the results of the rupture tests on the first lot of stock tested, heat 43642, became available, it was evident that the rupture strength at 1,500° F was considerably below normal (table II and fig. 4). Because preliminary overheat tests indicated the surprising result that no damage resulted from overheating in the absence of stress to 1,900° F, the NACA Subcommittee on Power-Plant Materials recommended that further experiments on this stock be stopped and material with normal rupture strength be obtained. This step was taken to avoid the possibility of erroneous conclusions due to some side effect related to abnormally low strength.

Three additional lots of bar stock, heats A-8133, 837, and A-9586, were checked and found to have low strength (table II and fig. 4). These were accordingly rejected from the experimental program.

At this point, stock from a vacuum heat, heat HT-28, was offered by the Haynes Stellite Co., which on the basis of their tests had somewhat higher strength than normal. This material was rerolled at the University of Michigan and tested at 1,500° F. The rupture strengths were found to be significantly lower (table III) than had been reported by the Haynes Stellite Co. In checking the reasons for the discrepancy, it was found that the material as tested by Haynes had been given a "mill anneal" at 2,150° F prior to the standard solution treatment at 1,950° F. When the stock rolled at Michigan was treated the same way, the strength values reported by Haynes were reached (table III).

The original rolling at Michigan had been carried out with a heating temperature of 1,950° F. The heating temperature was raised to 2,150° F in view of the information covered in the previous paragraph and after consultation with members of the NACA subcommittee. This raised the rupture strength somewhat (table II) but did not give so high values as when the 2,150° F mill anneal was used prior to solution treatment. It was decided, however, to carry out the experimental overhear investigation of M-252 alloy using material from heat HT-28 rerolled from 2,150° F at Michigan without the mill anneal. This procedure was agreed upon with the NACA subcommittee because the use of such preliminary high-temperature treatments was not standard practice in heat-treating blades for jet-engine gas turbines. In addition, the strength properties were closer to average accepted properties for the alloys.

The disclosure of the rather pronounced effect of the high-temperature treatment prior to the standard solution and aging treatment on creep-rupture properties at 1,500° F apparently was of considerable practical significance. It is also evident from the data that conditions of hot-working had some effect on response to final heat treatment. It is not known now to what degree these two factors were responsible for the relatively low strength of the stock from the first four heats checked for the investigation and how much was due to chemical composition and melting-practice effects. Heat 43642 had considerably lower titanium and aluminum content than the other four heats (table I). There does not, however, seem to be an obvious reason in the reported analyses for the superiority of heat HT-28 over the other three heats. Vacuum-melted heat 837 was stronger than the three air-melted heats (fig. 4) but was still considerably weaker than heat HT-28. It seems most probable that all factors were involved but that a major factor was the influence of working conditions on response to heat treatment.

As discussed in the section entitled "Procedure," the stock was rerolled at the University of Michigan with the intent of producing material with highly reproducible rupture times between specimens. While this procedure was quite successful for S-816 (ref. 1) it was not so successful for M-252 alloy. The rupture data at 1,500° F for

heats HT-28 and 43642 have been shown in figure 5 to show the range in rupture times at the stresses used for overheat experiments. These represent from 75 to 130 percent of the average rupture life at either of the two stresses used for heat HT-28 and from 70 to 115 percent at the stress used for heat 43642.

The results of the rupture tests conducted at the overheat temperatures for heat HT-28 are given in table II and are shown graphically by figure 6. A few tests also conducted on heat 43642 gave the results included in table II. The number of tests conducted on heat HT-28 at the higher temperatures was far less than would have been desirable. The limited amount of stock available, however, prevented more testing. The rupture times were rather short because the stresses used during the overheat tests under stress were selected to cause significant damage during the brief overheat exposure and thus were relatively high.

Overheats on Heat HT-28

The major portion of the program was carried out on heat HT-28. This included overheating in the absence of stress both cyclically throughout the test and as a preheat to the overheat temperatures before testing as well as overheating in the presence of stress cyclically during the test.

Overheating in absence of stress.- Overheats to 1,650°, 1,800°, 1,900°, and 2,000° F were conducted in the absence of stress. Stresses of both 24,000 psi (stress for rupture in 490 hours) and 34,000 psi (stress for rupture in 80 hours) were used at 1,500° F. In all of these tests the load was removed and the specimen overheated for 2 minutes, cooled back to 1,500° F, and reloaded every 12 hours for the tests under 24,000 psi. For the 34,000-psi tests the overheats were applied every 5 hours. Tests on the material exposed to the overheat temperatures before testing were all run at 34,000 psi at 1,500° F. Load cycling without temperature change at 1,500° F was also studied to determine how much effect the removal and reapplication of the load had on rupture time.

In addition to the changes in rupture time due to overheating, information was obtained on its effect on elongation in the rupture tests, on the creep curves, and on hardness as follows:

Effect on rupture life at 1,500° F of overheating in the absence of stress: The data (table IV and fig. 7) show that when the stress was removed from M-252 alloy during a rupture test at 1,500° F and the specimen briefly heated to higher temperatures, cooled back to 1,500° F, and restressed the resultant effect was dependent on the temperature to which the overheating was carried out and to some extent on stress which was

present at 1,500° F between the overheats. Figure 7 is drawn to show the estimated average effect of the overheating as indicated by the available data. The curves as drawn are extended to the limiting line which represents the maximum number of overheats which could be obtained at any time using the fixed cycles which were employed. Since the results are plotted here in terms of the percentage of normal life represented by a given test result, three lines are shown to account for inherent scatter in the rupture data. These lines represent the rate of accumulation of overheat cycles for minimum-, average-, and maximum-strength material indicated by figure 5 as various percentages of its life are attained. The curves which represent the effect of overheating on rupture time are thus terminated as they reach these limiting lines.

The following effects are indicated in figure 7:

(1) Overheating to 1,650° or 1,800° F resulted in a decrease in life which became greater as the amount of overheating increased. This decrease was of approximately the same order of magnitude at both of the two stresses used when the results were considered on a percentage basis. One sample at each of the two stresses appeared to show some increase in life as a result of the overheating. This was shown for the test which received the maximum number of overheats to 1,650° F under a stress of 34,000 psi at 1,500° F and for the test which received the maximum number of overheats to 1,800° F under a stress of 24,000 psi at 1,500° F. Consideration of the creep data from these two tests, however, indicated that these two points may be the result of abnormally strong specimens, and it is not believed that they indicate a reverse in the trend of the data as a result of prolonged overheating.

(2) Overheating cyclically to 1,900° or 2,000° F resulted in every case in an increase in life. The percentage increase was greater for those tests which were run at 34,000 psi than for those which were run at 24,000 psi. The actual difference at the two stress levels was not great by comparison with the magnitude of the effect itself. The difference may reflect less benefit from overheating in tests at lower stress and longer time, or some influence of the cycle frequency which was employed, or a combination of the two. The amount of increase in life which resulted from overheating to these temperatures was greater as the amount of overheating was increased, and appeared to continue to increase with further overheats over the entire range of overheat times considered.

(3) One way to appreciate the magnitude of the effect of overheating is to consider the change in rupture strengths at 1,500° F indicated by the data. Figure 8 shows the curves of stress against rupture time drawn from results of the overheat tests for the maximum extrapolated effects (i.e., for tests continuously overheated to rupture) compared with the normal curve at 1,500° F for heat HT-28. The plotted points represent the maximum average effect of overheating to 1,650° or 1,800° F where

overheating resulted in damage and the maximum average effect of overheating to 1,900° or 2,000° F where overheating resulted in an improvement in rupture life. These curves were obtained from figure 7 by extrapolation of the indicated curves to the maximum number of overheats which could be obtained with the cycles employed. These curves indicate the following values of rupture strengths for the conditions outlined above:

| Overheat temperature, °F | Stress for rupture, psi, at 1,500° F, in. - (a) | |
|--------------------------|--|----------|
| | 100 hr | 1,000 hr |
| None | 33,000 | 21,000 |
| 1,650 or 1,800 | 29,500 | 19,000 |
| 1,900 or 2,000 | 40,000 | 24,000 |

^aThese stresses assume a total of 20 2-min overheats with 100-hr rupture stress and 83 2-min overheats with 1,000-hr tests, according to the cycles outlined above.

These are the maximum effects indicated. Lesser amounts of overheating would change the strength less. Consideration of these rupture strengths is perhaps more realistic than consideration of the rupture times which are subject to much wider variations. It should also be recognized that the frequency of overheating could influence the results, and the above values are for the specific conditions used in the tests.

(4) The data obtained on material preheated to the overheat temperatures and then rupture-tested in a normal fashion at 34,000 psi and 1,500° F are presented in table V and are plotted for comparison in figure 7. The preheat times selected were accumulated times at the overheat temperatures which had given substantial effects in the cyclic overheats. All of these tests resulted in rupture times shorter than that for a normal rupture test at the same stress and temperature, with the higher temperatures of preheating resulting in the shortest times. It had been previously noted that cyclic overheating for the same total times at 1,900° and 2,000° F resulted in an increase in life compared with that for a normal rupture test. This indicates that for the strengthening effect to occur, the overheating must be applied in fairly small increments with some interval of time at 1,500° F under stress between cycles.

(5) In all of the above cyclic tests, the load was removed during the overheats, introducing the possibility that the cycling of the stress

alone could have had an effect on the rupture time. One test was run at 1,500° F and 24,000 psi in which the load was removed and reapplied at 1,500° F without changing the temperature at the same frequency as in the cyclic overheats at this stress. The rupture time obtained of 382 hours was 78 percent of the normal time at this stress (table IV and fig. 7). This is at the lower edge of the scatter band and may possibly indicate that there was some reduction in rupture life from the load cycling.

Effect on elongation of overheating in the absence of stress: Measurements of total elongation at fracture are included in tables III and IV for each condition of overheating. Figure 9 shows these data for cyclic overheating in the absence of stress and for preheating. The following generalities are indicated:

(1) Overheating to 1,650° F at either of the two stresses used gave elongation values in the range of values for normal rupture tests.

(2) Overheating to any of the other three temperatures resulted in a decrease in elongation as the amount of overheating increased, with the values being definitely lower than the scatter band for normal rupture tests. This decrease in ductility occurred at shorter times of overheating for overheats to 1,800° F than it did for tests at the two higher temperatures.

(3) Of the three tests which were preheated, one fell just above the normal range, and the other two were in the range.

(4) Although the load cycling at 1,500° F may have resulted in a slight decrease in the rupture time, it did not affect the elongation.

Effect on creep curves of overheating in the absence of stress: Creep data were taken for all tests. The time-elongation plots of these data are presented in figures 10 and 11. In these figures the points noted in the key as overheats represent the measurements taken before and after one overheat cycle. Points noted as standard creep readings are routine measurements taken when overheats were not being applied. In evaluating the data from these curves consideration must be given to the apparent variation between samples which seems to exist. The following generalities were developed after a critical evaluation of each curve when it was considered relative to the other curves from tests under similar conditions. Ideally, of course, all of the curves for a given overheat temperature should be identical up to the point at which the overheating was discontinued. Some deviation from this situation is to be expected in any case, but when the magnitude of the difference becomes large, allowance must be made in evaluating their significance. On this basis then the following comments may be made about these creep curves:

(1) Load cycling at 1,500° F (fig. 10) resulted in a creep curve with a higher creep rate than did the normal creep test at the same stress. The difference in rate between these two tests is somewhat marginal in its significance. The two curves do not differ by more than could be expected for duplicate tests because of variation between samples and do not indicate definitely that there was a significant effect from the load cycling.

(2) The creep curves from tests run at 24,000 psi and overheated twice a day in the absence of stress (figs. 11(a) to 11(d)) indicate the following general trends:

(a) Overheating to 1,650° or 1,800° F resulted in an immediate increase in the creep rate. This increase continued so that the curves remained above that for a normal creep test. Because of the incompleteness of the data, the effect of discontinuing the overheating is not well established.

(b) Overheating to 1,900° or 2,000° F resulted in a higher creep rate in the early portion of the test than was shown by a normal creep test. This rate, however, remained essentially the same while the rate in the normal test increased with time. Thus, after about 200 hours of testing, the test on the specimen which had been overheated showed less total deformation than the normal curve. When overheating to these two temperatures was discontinued, the creep curve continued at approximately the same rate as it had shown during the overheats and gradually exhibited an increase in creep rate over that shown for a test which was continuously overheated, approaching the rate for a normal creep test at the same total deformation. Apparently both of these temperatures influenced the creep curves in the same way.

(3) Tests run at 34,000 psi on specimens overheated every 5 hours in the absence of stress produced the following effects on the creep curves (figs. 11(e) to 11(h)) as a result of the overheating:

(a) Overheating to 1,650° or 1,800° F resulted in an increase in the creep rate over that for a normal creep test with the effect being the same for both temperatures of overheating. The limited data also indicate that when overheating was discontinued, the creep rate decreased to a lower value.

(b) Overheating to either 1,900° or 2,000° F initially increased the creep rate over that for the normal test. As was the case for the tests under 24,000 psi, however, this creep rate continued at a nearly constant value while the rate in the normal test increased. This resulted in a crossing of the curves at about

30 hours. Beyond this time the test on the overheated specimen showed less total deformation at any given time than did the normal test.

(4) The above generalities regarding the effect of overheating on the creep curves were made after a consideration of all of the curves at each overheat temperature. In some instances individual curves deviated from the general pattern and were excluded from consideration. Previous mention has been made regarding the rupture times resulting from these tests.

In particular, the sample under 34,000 psi at 1,500° F which received 18 overheats to 1,650° F, (fig. 11(e)) and that under 24,000 psi at 1,500° F which received 42 cycles to 1,800° F (fig. 11(b)) appeared to be abnormally creep resistant. Both showed creep rates much lower than any of the other tests at the same testing conditions.

(5) Preheating to the overheat temperatures and then testing at 34,000 psi (fig. 12) gave creep curves which were in every case higher than the normal curve. The deviation of these curves from that of the normal test became greater as the preheat temperature increased.

Effect on the time to reach a given total deformation of overheating in absence of stress: Figure 13 shows the time to reach a given total deformation as a function of the overheat temperature for tests on specimens overheated in the absence of stress twice a day with 24,000 psi present at 1,500° F. These curves were compiled from estimates of the best average curve at each overheat temperature using the data from figures 11(a) to 11(d) as a guide. The following points may be noted from figure 13:

(1) Every deformation considered was reached sooner when the load was cycled at 1,500° F than it was in the normal creep test.

(2) The time to reach any total deformation decreased further as the temperature of overheating increased up to 1,800° F. The times for 1,650° and 1,800° F overheating were the same, however, at 4 or 6 percent.

(3) Overheating to 1,900° F increased the time to attain all of the values of deformation over that which was shown at 1,800° F. At 1 percent the time was about the same as that for a normal creep test, while at 2 percent and higher values it became longer than for the normal test.

(4) Overheating to 2,000° F caused a reversion to shorter times for low deformation (up to about 4 percent). The time to reach 1 percent was shorter than that for the normal test. At 6 percent the time was the same for 1,900° and 2,000° F. This reflects the fact that the creep curves for these two overheat temperatures cross each other at about

6-percent total deformation. It should be kept in mind that this figure is specifically indicative only of results obtained using the cycles employed for these tests, that is, one overheat twice a day from the start of the test in the absence of stress, with the stress at 1,500° F being 24,000 psi.

Effect on hardness of overheating in the absence of stress: Vickers hardness was measured on several of the specimens which had been used in the various portions of the investigation. The results of these measurements (fig. 14) indicate the following things:

(1) Hardness of samples after normal rupture-testing indicated a decrease in hardness as the testing temperature increased to 1,900° F, with the test at 2,000° F giving a hardness equivalent to that obtained from testing at 1,500° F.

(2) The samples subjected to overheating showed that those conditions resulting in a decrease in rupture time produced little change in hardness over the samples rupture-tested at 1,500° F. When testing conditions resulted in an increase in strength, the hardness was lower than that of the 1,500° F rupture tests.

Overheating in presence of stress.- The purpose of overheating in the presence of stress was to determine if the postulated relationship between the effect of temperature and stress could be used to account for the actual rupture times obtained. Although the amount of testing was rather limited, the entire temperature range of the investigation was covered (table VI). The general approach was to determine if the calculated amount of rupture life used up by creep at the overheat temperature plus the effect of the overheat temperature itself would account for the experimental rupture times. Proof or disproof of this possibility was thought to be the best way to develop general principles from the relatively few tests possible within the limitations of the program. The following considerations were investigated:

Correlation between predicted and actual rupture time for tests of specimens overheated under stress: It was postulated that the rupture time for overheating in the presence of stress would be changed from that of a normal rupture test at 1,500° F by the sum of two effects:

(1) The change due to exposure to the higher temperatures as established by figure 7.

(2) The reduction of rupture time to be expected from the creep due to the presence of stress during the overheat. This was estimated as the fraction of life used up at the overheat temperature and was calculated by dividing the total time under stress at the overheat temperature by the normal rupture time under stress at the overheat temperature

as determined from figure 5. The total time at the overheat temperature was obtained by summing the number of 2-minute overheats which were applied.

The data for the tests with stress present during the overheats are given in table VI. Using the data of figures 6 and 7, predicted rupture times were computed for the tests to check on the postulated method of estimating the effects of overheats in the presence of stress. The details of the calculations will be presented later. The results of the calculations (table VII) show that the actual rupture times were much longer at 1,650° and 1,800° F than was estimated. When overheating was carried out to 1,900° and 2,000° F, the estimated and actual values were in very close agreement.

The anomalies for overheating to 1,650° and 1,800° F are reflected in two ways. Calculations of the number of possible overheats, taking into account the variation in normal rupture time between specimens at 1,500° F (fig. 5), gave numbers which were less than the number of overheats actually imposed on the specimens, even though overheating was actually discontinued before fracture. In addition, the actual times were longer than the theoretical maximum time for specimens with the highest strength indicated by figure 5.

The average normal rupture time at 1,500° F for the 24,000-psi stress used in the tests was 485 hours. Thus in all tests except those overheated to 1,650° F there was a significant increase in rupture time from overheating even though a substantial stress was present during the overheats. This is a rather striking effect. If, for instance, the only effect involved had been the rupture life used at the overheat temperature, the rupture time would have been reduced as follows:

| Overheat conditions | | | | Rupture life used at over- heat condi- tions, percent | Expected remaining rupture time at 1,500° F and 24,000 psi, hr |
|-------------------------|----------------|---|--|--|---|
| Temper- ature, °F | Stress, psi | Normal rupture time at over- heat stress, hr | Total time at overheat stress, min | | |
| 1,650 | 24,000 | 9.2 | 60 | 11 | 432 |
| | 30,000 | 2.9 | 50 | 29 | 345 |
| 1,800 | 8,000 | 5.2 | 78 | 25 | 364 |
| | 10,000 | 1.6 | 60 | 62 | 184 |
| 1,900 | 5,000 | 9.0 | 110 | 20 | 388 |
| 2,000 | 4,000 | 4.5 | 66 | 24 | 369 |

It is to be clearly understood that if sufficiently high stresses had been used during the overheats, the creep damage could be made to predominate and to reduce rupture life. The maximum effect of this type would be when the stress exceeded the tensile strength and caused fracture during the first overheat.

These values indicate that some factor associated with the overheat temperatures increased rupture life by offsetting the creep damage due to stress during the overheats. This was somewhat less than the creep damage in the overheats at 1,650° F and more than the creep damage at the other three temperatures. This was not unexpected for overheating at 1,900° and 2,000° F because the preceding discussion had shown that cyclic exposure to these overheat temperatures increased rupture life at 1,500° F. The increases in life made by heating to 1,650° and 1,800° F were, however, unexpected. Overheating in the absence of stress had shown reduction in rupture time at 1,500° F. Both the temperature and the stress effects had been expected to contribute to reduced life.

This means that the effects of overheating at 1,650° to 1,800° F cannot be estimated on the basis of the hypothesis advanced. Apparently, rupture times will be longer than would have been anticipated. Unidentified additional factors must have been introduced by overheating in the presence of stress in this temperature range. The hypothesis advanced seems, however, to work very well for overheating at 1,900° to 2,000° F, which suggests that no additional factors were involved at these temperatures.

The following possibilities are suggested as reasons contributing to the lack of predictability for tests overheated in the presence of stress at 1,650° to 1,800° F:

(1) It may be that the rupture time at these temperatures is considerably different when heated from 1,500° F in a few seconds than when 4 to 5 hours are used for temperature adjustment before loading as is the procedure for the normal rupture tests.

(2) The prior exposure to stress at 1,500° F and the temperature effects of overheating increased strength at 1,650° and 1,800° F by structural alterations over that of as-heat-treated specimens.

(3) Data scatter may simply be obscuring the results. This seems unlikely, however, because the inherent strength of the specimens used for the overheats at 1,800° F would have to be far higher than indicated by any of the data to account for the observed results.

(4) It is also considered unlikely that the presence of stress during the overheats changed the temperature effect of overheating from reduced to increased rupture life at 1,500° F.

Method of calculation of estimated rupture times: The postulated effects of overheating under stress can be expressed by the following formula:

$$t_o = t_n(f_t - f_s)$$

where

t_o time to rupture for overheating in presence of stress
 t_n normal rupture time at 1,500° F
 f_t rupture time for overheating with stress removed divided by t_n
 f_s time at overheat temperature under stress divided by normal
 rupture time at overheat temperature under stress

It should be noted that the term $(f_t - f_s)$ represents the fractional reduction in rupture time to be expected. The values for f_t are obtained from figure 7 as decimal fractions. The values of f_s are obtained by summing the time at the overheat temperature and dividing by the expected rupture time for the stress as defined by figure 5.

Two types of calculations of expected performance were carried out as follows:

(1) The theoretical maximum amount of overheating was calculated for test conditions if overheating was continued to rupture. This required a trial-and-error solution. A number of cycles was assumed and the f_t and f_s factors computed. This assumed number of cycles was adjusted until the number of cycles agreed with those theoretically possible under the fixed schedules used. This was done for the minimum, average, and maximum rupture times at 1,500° F as defined by figure 5 so that the range of significance would be established. This procedure then indicated the range in the amount of overheating which could have occurred if the postulated mechanism was valid. In addition, it gave rupture times which would be expected for the conditions.

The test results (table VII) showed that when overheating was carried out at 1,650° and 1,800° F a larger number of overheats was actually imposed than was theoretically possible under the postulated basis for calculation. This occurred even though overheating was stopped before rupture. This simply means that factors other than those considered operated at these temperatures.

(2) For the tests at 1,900° and 2,000° F, overheating was stopped before fracture and before the theoretical number of possible overheats had been imposed. Therefore, in order to calculate the predicted rupture time, values of f_t for the actual number of overheats were obtained from figure 7 for average test material and similar calculations of the value of f_s were made. The close agreement between predicted and actual rupture times for average material indicated that calculated values based on the range in strength were not necessary to demonstrate that the hypothesis held for those tests.

In evaluating the method of calculating predicted life, care should be taken to appreciate clearly the assumptions and limitations involved. The more important of these are:

(1) The basic assumption was that the effect of overheats under stress was the direct sum of the structural change effects from temperature and the effects of creep at the overheat temperature.

(2) The creep damage from successive 2-minute overheats was assumed to be cumulative and directly additive.

(3) Until more extensive studies are available to check the effect, it cannot be assumed that the effects are independent of the cyclic schedule of overheating. This schedule was twice a day. The temperature effects as well as the addibility of accumulative time under stress at the overheat temperature might be different for other schedules of overheating.

(4) In computing the effect of temperature during the overheats from figure 7, any variation due to specimen variation was ignored. Only the average curves were used. The data were not sufficiently complete to warrant any attempt to take this into consideration although the data do indicate that it may have been a considerable factor. It would not, however, be enough to account for the disagreement between calculated and actual values for the overheats to 1,650° and 1,800° F.

(5) It was assumed that the effect of temperature during overheats would have the same percentage effect independent of variation in the initial strength of specimens. In other words, the same values from figure 7 were used for computing the change in rupture times for specimens with minimum, average, and maximum strengths within the observed ranges.

(6) The normal rupture data in figure 5 were obtained on specimens which were brought to the testing temperature and held 4 hours before applying the stress. It is possible that the rapid heating rates used in the overheat tests resulted in an available rupture life at the

overheat temperatures which was longer than that indicated by figure 5. This would not, however, account for the entire discrepancy since this effect would merely be to decrease the amount of the stress damage and could not, in any case, result in an actual rupture time greater than the normal time.

Effect on creep curves of overheating in presence of stress: The creep curves for the tests overheated in the presence of stress (fig. 15) indicate the following results:

(1) Overheating to 1,650° F resulted in curves which exhibited higher creep rates throughout their life than the normal curve at the same stress. The degree of acceleration was the more the higher the stress.

(2) Overheating under stress to 1,800° F appeared to result in a strengthening of the material so that, even in the presence of stress, the creep curve did not attain so high a rate as did the curve from a normal creep test. The sample which carried the higher load during the overheating showed the higher overall creep rate of the two tests run.

(3) Overheating to 1,900° or 2,000° F resulted in the creep curves shown in figure 15(b). Although the effect of the stress which was present during the overheats was to cause deformation during each overheat cycle, the creep curves show a lower creep rate after several cycles than the normal curve for a test under the same stress at 1,500° F. These curves also show that there is an increase in the amount of deformation during each overheat cycle as the amount of prior deformation was increased.

Microstructural effects.— Samples representing most of the test conditions employed in this investigation were examined microscopically. A careful review of the structures resulting from the overheating, as observed with the optical microscope, revealed that the apparent structure after any of the testing conditions was essentially the same. That is, the light microscope was unable to detect any significant difference in the structures of the overheat samples as compared to those resulting from specimens simply rupture-tested at 1,500° F for comparable times. A few of the structures are shown (figs. 16 and 17) to point out the similarity of structures for widely divergent overheat conditions and effects on properties from overheats.

Overheats on Heats 837 and 43642

A few overheat tests were conducted on specimens from heats 43642 and 837 prior to the time it was decided not to use them for the bulk of the experimental program.

Overheats in absence of stress.— One specimen from heat 43642, subjected to load cycling at 1,500° F, indicated a possible considerable reduction in rupture time (table IV). Another specimen indicated practically no change in rupture time (table IV) as the result of overheating to 1,900° F with the load removed during the overheat periods. There apparently was considerable variability in rupture time at 1,500° F between specimens from this heat for stresses of about 14,000 psi (fig. 4). It is therefore doubtful that much significance should be attached to the exact values of rupture time for the tests with cyclic loads and overheats to 1,900° F. It does appear, however, that the results are of the same type as those for the more extensive tests discussed for heat HTP-28: (1) There was some reduction in rupture strength from load cycling alone at 1,500° F, and (2) there was a probable increase in life at 1,500° F from overheating to 1,900° F with the load removed. Within the data scatter indicated in figure 4, both tests could have checked the results previously given for heat HTP-28 on a percentage basis. Certainly, on the basis of the limited experimental data, it could not be concluded that there was much effect from overheat tests normally lasting 1,200 hours at 1,500° F when compared with those run on heat HTP-28 using shorter normal rupture times.

One test of a sample from heat 837 cyclically overheated to 1,900° F with the stress removed showed an increase in rupture time which was somewhat less than had been previously obtained on heat HTP-28 (table IV). It is uncertain whether or not this one test showing a smaller effect than heat HTP-28 significantly indicates a difference in the response to overheating. More tests would be required to be sure. It should also be noticed that this heat had a comparatively steep stress-rupture time curve (fig. 4) in comparison with those of heat HTP-28 or the other materials tested.

Duplicate tests on specimens from heat 43642 involving heating for 4 hours at 1,600° F before testing (table V) showed at most a slight reduction in rupture time. This is similar to the effect found for 20 minutes of preheating to 1,650° F for heat HTP-28 (table V).

Overheats of heat 43642 in presence of stress.— Five tests were conducted using heat 43642. Three of these tests were on specimens overheated to 1,600° F for 2 hours in one cycle. One specimen was overheated during first-stage creep (after 142 hours at 1,500° F), and the other two, after second-stage creep had been well in progress (after 404 and 456 hours at 1,500° F). The results (table VI) showed little change for two of the tests. The other test (overheated after 404 hours at 1,500° F) indicated a pronounced reduction of life. Data are not available to estimate the effect of temperature for the 2 hours at 1,600° F on subsequent rupture life at 1,500° F, except that it was probably small. The 2 hours at 1,600° F under the stress used were so small a part of the total available rupture life that their effect on time at

1,500° F was negligible. It now appears that the two tests indicating little effect are probably correct and the specimen which broke prematurely was probably subject to some unrecognized experimental error or was related to the rather excessive scatter in rupture time indicated by figure 4 for specimens from this heat.

The test on specimens overheated to 1,800° F lasted less time than anticipated. It should be recognized, however, that, because the normal rupture time at 1,800° F was so short, only a small error in the normal rupture time would be required to cause this difference. Only one rupture test was run at 1,800° F. This probably was slightly long and therefore led to a longer predicted life than was available as could easily be the case for material with as much scatter in rupture time as for this heat. The data from figure 7 indicate that any effect of temperature alone from two overheats to 1,800° F was negligible.

The test on the specimen overheated to 1,900° F was under such a high stress that it was near to the tensile strength at 1,900° F and used up all of the rupture life very rapidly. The total time at 1,900° F in the overheat test agrees very well with the predicted rupture time at 1,900° F as determined in a normal rupture test.

Comparative Effects of Overheating on S-816, HS-31, and M-252 Alloys

From the viewpoint of probable response to overheating, M-252 alloy is basically different from either S-816 or HS-31 alloy. The latter two alloys are cobalt-base materials which appear to be essentially dependent for variation in high-temperature strength on the degree of solution of alloying elements having odd-sized atoms. The major precipitates which form during aging or testing, M_4C and M_6C types of compounds, probably reduce strength by removing odd-sized atoms from solution. M-252, on the other hand, is a nickel-base alloy hardened with titanium and aluminum. It contains the complex $Ni_3(Al,Ti)$ precipitates and presumably depends largely for its strength on the presence and distribution of these precipitates. Thus it would seem likely that the responses of these two types of material to overheating would differ.

For the purpose of comparison of the three alloys, the results of overheating in the absence of stress from the previous work on S-816 (ref. 1) and HS-31 (ref. 2) have been replotted together with the results of the present investigation. Consideration of this figure (fig. 18) indicates the following general effects:

(1) Overheating to $1,650^{\circ}$ F in the absence of stress (figs. 18(a) and 18(b)) appeared to damage M-252 the most. Small amounts of overheating may have slightly increased the life of S-816 and HS-31 alloys. Both of the latter two alloys showed a fall off in rupture strength with continued overheating.

(2) Overheating to $1,800^{\circ}$ F at the higher of the two stresses used for each alloy gave approximately the same effect for all three when the results are considered on a percentage basis. Damage occurred and was greater the longer the duration of the overheats. At the lower of the two stresses, the effect of a few overheats was essentially the same. The rate of damage for S-816 and HS-31 alloys was greater, however, and at the longer times of overheating the M-252 showed less damage than either of the other two materials.

(3) At temperatures of $1,900^{\circ}$ and $2,000^{\circ}$ F, the amount of damage became very large for S-816 and HS-31 alloys even for relatively short times of overheating. On the other hand, the M-252 alloy showed an increase in rupture life as overheating was carried out to these temperatures with the increase becoming greater as longer times of overheating were employed. It should be recognized that these comparisons are presented on a basis of the percentage of the normal rupture life under the stresses which were employed, and do not accurately reflect the actual relative load-carrying ability of the three materials. Thus, even though M-252 showed the most damage of the three alloys when overheated to $1,650^{\circ}$ F, its superior strength at high stresses would result in maintenance of its superiority at short rupture times, if all materials were considered on the basis of the same stress. Of major significance in this comparison is the fact that M-252 alloy showed an increase in strength after overheating to $1,900^{\circ}$ or $2,000^{\circ}$ F whereas the other two materials suffered their most severe damage at these two temperatures.

When overheating occurred in the presence of stress, creep damage was added to the effect of temperature on the properties at $1,500^{\circ}$ F. The combination of these two effects on M-252 alloy resulted in less reduction in life at $1,500^{\circ}$ F than would be anticipated from rupture strengths at the overheat temperatures. S-816 and HS-31 alloys both were reduced more in strength than the percentage of rupture life represented by the time at the overheat temperature. Thus, the major difference between M-252 alloy and S-816 or HS-31 alloys was the increase in life of M-252 from the temperature effect while the lives of the latter two alloys were reduced.

The governing factor in the relative ability of the three alloys to withstand overheating under stress was the combined effect of temperature during overheating on properties at $1,500^{\circ}$ F and the amount of creep-rupture life used up during the overheat period. The temperature

effects have previously been discussed. The creep-rupture damage depends on the relative creep-rupture strengths at the overheat temperature for the stress existing.

The curves of stress against rupture time for the three alloys at the overheat temperatures used in this investigation are compared in figure 19. The M-252 material tended to have higher strength under high stresses and short times for rupture. This superiority decreased with increasing time for rupture and increasing temperature, so that its rupture strength was generally inferior to that of the other two alloys at 1,900° and 2,000° F. The HS-31 material had better strength than the other two alloys for the longer times and higher temperatures of heating.

The relative ability to withstand overheating in the presence of stress for the three alloys then was dependent on the time and temperature of overheating and the stress present. In general terms it can be stated that:

(1) At relatively low temperatures of overheating with high stresses, M-252 alloy should be most resistant because of its relatively high rupture strength under these conditions. Also the temperature effect will be small and the relative rupture strengths under the overheat conditions will be the governing factor.

If the stresses are lower and overheating much longer, then the higher rupture strength of the other alloys under these conditions should become the governing factor and reduce the difference and even develop superiority for the other alloys.

In this connection, however, it must be considered that the overheat tests on M-252 alloy at 1,650° and 1,800° F under stress showed less damage than was anticipated. Until more data involving this anomaly are available, it cannot be said with certainty that M-252 alloy would become inferior even for long-time overheating with relatively low stress.

(2) The lowered rupture strength of M-252 alloy with increasing temperature, particularly in comparison with that of HS-31 alloy, is offset by the increased life from the temperature effect. The increase in life at 1,500° F from the temperature effect of overheating predominates for overheating to 1,900° and 2,000° F until the time under stress during overheating uses up a substantial part of the total life. Thus M-252 becomes inferior at these temperatures only when overheating times are long or when stresses are high.

The lower rupture strength of S-816 alloy in comparison with that of HS-31 alloy is partly offset by the smaller temperature-damage effect. Again, therefore, it becomes inferior when the creep damage becomes the

predominate factor, that is, at high temperatures and longer times of overheating in relation to the total possible time under stress at the overheat temperature.

Two sets of figures have been prepared to illustrate the relative abilities of the three alloys to withstand overheating in the presence of stress as indicated by references 1 and 2 and from this investigation. These figures show the combined effect of the temperature cycling and the stress which is present during the overheat and were prepared using the averages of all of the effects involved as indicated by the available data as follows:

(1) Figure 20 shows the rupture time as a function of the stress during the overheats for specific times of overheating to each of the four temperatures considered. The basis selected for comparison was a 500-hour rupture test at $1,500^{\circ}\text{F}$ for all three alloys. The stress at $1,500^{\circ}\text{F}$ was, therefore, that causing rupture in 500 hours in a normal $1,500^{\circ}$ rupture test. The intersection of the plotted curves with the zero-stress axis represents the effect of temperature alone as previously determined. Those cases where this intercept is greater than 500 hours result from overheat conditions which caused an increase in rupture life. The dashed line at which all of the curves terminate represents the restriction imposed by the fixed cycling schedule under which the previous data were accumulated (two overheats of 2-minute duration twice a day). That is, for example, a curve representing the effect of 40 minutes of overheating cannot drop below the time required to accumulate 20 overheat cycles, or 240 hours. This dashed line thus represents the locus of all points resulting from imposing the maximum possible number of overheats before rupture occurred.

All of the curves shown were calculated using the same procedures outlined in the section "Overheating in the presence of stress." Since the proposed method of calculation did not work for M-252 alloy at $1,650^{\circ}$ and $1,800^{\circ}\text{F}$, as previously discussed, no curves are shown for these conditions. Only the few actual data points are included.

(2) The curves in figure 21 are taken directly from figure 20 and regrouped for specific overheat times to provide an easier comparison of the three alloys.

Consideration of these figures indicates good agreement with the generalities previously postulated from the effects of overheating in the absence of stress and the comparative curves of stress against rupture time at the overheat temperatures.

It should be kept in mind with reference to these figures and the above generalities concerning them that the data from which they were drawn contain rather specific limitations. Only one heat of material

with one heat treatment was considered for each alloy and as heat-to-heat differences occur they could influence the relative effects of any given condition of overheating. Furthermore, the particular schedule of overheating which was considered may influence the magnitude of the temperature effects. The data on which the calculations were based were all taken with overheats twice a day beginning at the start of the test. A change in cycle frequency or duration, or a delay of the initial cycle, may influence test results. In addition, since the curves of stress against rupture time for these three alloys are not parallel, the relative strengths at 1,500° F are a function of the rupture time which was chosen for comparison. At 500 hours, the time period chosen above, by coincidence both M-252 and HS-31 had the same strength at 1,500° F and were both stronger than S-816. At shorter times, the M-252 would have been strongest, while for longer times HS-31 would predominate.

The generalities presented, then, are specifically valid only for the particular conditions under which they were evaluated, and care should be exercised in applying the data except in their general form.

Mechanism of Damage From Overheating

The overall effect of an overheat appears to consist of two components: (1) The effect of the structural alterations as a result of being exposed to the higher temperatures; and (2) the rate at which creep-rupture life is used up when stress is present during an overheat.

The damage due to the presence of stress during an overheat appears to be simply a case of using up the available rupture life by creep. The reasonable success of the addibility of rupture-life fractions indicates that there is no great difference in the mechanism by which creep life is used up over the overheat temperature range considered in the investigation.

The mechanism for temperature effects is less certain. It is most certainly related in some way to structural alterations induced by the overheat temperature during the periodic exposures. Since the optical microscopy used in this work did not reveal any differences in the structures of the various samples after rupture had occurred, at this time only a postulation of the possible mechanism can be made. Presumably, the amount, size, and distribution of the $\text{Ni}_3(\text{Al,Ti})$ precipitates are the controlling factors in the strength of the alloy. If the precipitate is taken into solution completely and then aged to an optimum dispersion the best properties are obtained. As testing is carried out in the range from 1,400° to 1,600° F these precipitates will agglomerate and overage, thus reducing their effectiveness in strengthening the material. This accounts for the steep slope shown by the curves of stress against rupture time for this type of material. That is, as lower stresses are used

which permit longer testing times, the overaging becomes more severe and the material becomes weaker than that on which the entire life of a shorter test was obtained.

The results of the present investigation are very likely related to this effect. Overheating in the absence of stress to temperatures up to 1,800° F may have resulted in an acceleration of the overaging and reduced the strength of the material at a higher rate than simple testing at 1,500° F. The higher temperature overheats on the other hand could then redissolve the precipitates to an extent sufficient to reduce the overaging reaction which normally occurs at 1,500° F. Since the duration of the overheat cycles was the same for all of the temperatures used, overheating to 2,000° F was able to redissolve more of the material in the fixed time than the overheats to 1,900° F.

The presence of stress during overheats to 1,650° and 1,800° F may have reduced the overaging from overheating. It is possible that at 1,800° F some re-resolution actually occurred.

It may be, therefore, that the effect of overheating on M-252 alloy is dependent on the relation of the overheat temperature to the solution temperature of the precipitates which are present. If conditions are such that severe agglomeration of the particles can be prevented, the material can actually show properties which are better than those for the same material considered in a normal stress-rupture test. This proposed mechanism is, however, at this stage purely hypothetical, and further work will be required to determine its exact nature.

Interpretation of Results in Terms of Overheating in a Turbine

The most striking feature of the experiments was the indication that overheating during service could prolong the creep-rupture life of M-252 alloy. There are, however, certain aspects of this finding which should be clearly understood:

(1) Overheats to temperatures from 1,650° to 2,000° F had relatively little effect on M-252 alloy when applied periodically during rupture tests at 1,500° F unless repeated a considerable number of times. The only exception to this was the case where stress was present and was of sufficient magnitude to use up significant amounts of creep-rupture life in a few overheats.

(2) In order to obtain a significant increase in rupture life from periodic overheats to 1,900° or 2,000° F, overheating for a number of times during the life of the turbine would be necessary. The stress present during overheats would also have to be low enough so that the

creep-rupture life used up during the overheats would not offset the increase in life from the temperature effect.

(3) The increase in rupture life from overheating to 1,900° and 2,000° F would be accompanied by reduced total creep only when the overheating was repeated a number of times. Creep was accelerated from a few overheats. Under the overheating conditions of the experiments, reduced creep from repeated overheating to 1,900° F was found only after the total deformation was 1 percent and more than 4 percent when overheated to 2,000° F.

(4) The combined effects of temperature and stress during overheats to 1,650° and 1,800° F would be less than anticipated from the separate evaluations of the two effects. Apparently some stress present during such overheats reduces damage from the temperature effect and under certain conditions of repeated overheating would prolong life in the turbine.

(5) Overheating before service to any of the temperatures considered will be damaging to service life in M-252-alloy parts. Experiments indicated that heating before testing to the same temperatures and total times that resulted in improvement in rupture life in cyclic tests always decreased the rupture time below that for a normal rupture test.

The results support the general conclusions of the two previous studies (refs. 1 and 2) that a few brief overheats during turbine life have very little effect on prospective creep-rupture life of turbine parts, unless stress high in relation to the rupture strength at the overheat temperatures is present. This suggests that, in general, significant effects on turbine performance from one or two overheats must arise from other effects, such as thermal shock or increased corrosion. There is one major exception to this in that S-816 and HS-31 alloys were significantly reduced in rupture life from one overheat to 2,000° F for 2 minutes (figs. 18(g) and 18(h)).

In contrast with the results for M-252 alloy, both temperature and stress during overheating can always be expected to reduce creep-rupture life of turbine parts for alloys of the type of S-816 and HS-31. As previously discussed the effects will be quite small, except for overheating to 2,000° F for S-816 and HS-31 alloys, unless an appreciable number of overheats should occur. Repeated overheating of M-252 alloy to 1,900° and 2,000° F tends to increase rupture time whereas it will further reduce rupture life of the other two alloys. In the presence of stress, the improvement from this source also apparently occurs in M-252 alloy for overheating to 1,650° and 1,800° F.

It should also be noted that overheating can influence only the life after overheating occurs. Thus if some significant part of the life had been used up at normal operating conditions, such as 50 percent, only the remaining potential 50 percent could be affected. Thus the overall effect

would be less than is indicated by this report which was based on tests overheated periodically from the start of the tests.

The estimation of the effects of overheating on the creep-rupture life of turbine parts is a fairly complex problem, as is demonstrated by the extensive interpretations necessary for this report. The report presents general concepts which should be useful for this purpose. Careful attention to detail is necessary, however, to obtain precise evaluations. While the general principles outlined seem valid, the estimation of the exact effects in any particular case is subject to some rather severe limitations as discussed in the next section.

Limitations of Results

Certain limitations of the results in terms of the generalities concerning effects of overheating should be clearly recognized:

(1) Fixed schedules of overheating were used. The indicated general effects of overheating might be considerably altered for some other schedules. In particular, more information would be desirable for the case where overheating was delayed after the tests started at 1,500° F. This type of information is very meager for a limited number of overheats.

(2) More information ought to be available regarding the effect of the duration of each overheat. As it now stands only 2-minute overheats have been studied. It seems reasonable to expect that there will be some point where the number of overheats as well as the total time of overheating will exert an effect on creep-rupture properties.

(3) Only the effect on creep-rupture characteristics at 1,500° F has been studied. Before the general principles are applied too widely it would be well to know how properties at other temperatures are affected. This possibly should also include effects when the stress at the normal service temperature was somewhat lower (i.e., longer rupture times than 500 to 1,000 hours).

(4) The data on the effect of stress during overheats are very limited. Considerably more data, particularly for M-252 alloy, are needed before the general method of computing combined effects is proven. Quite probably, wider investigation of this subject would show other deviations than the one found for M-252 alloy when overheated to 1,650° and 1,800° F under stress.

(5) Reference to figure 3 shows that during each overheat cycle there was a certain amount of time during the heating and cooling portions of the cycle that the test sample was between 1,500° F and the overheat temperature. The measurements made on the effects of

temperature alone, however, in every case include whatever influence this time exerted. Similarly, since the cycles were identical, the effect of temperature alone during an overheat in the presence of stress could be accurately evaluated from the previous data taken in the absence of stress. The one possible source of error was that the presence of the stress used during the overheats in this heating and cooling time may have introduced an error in the calculation of the amount of life used up by creep during each cycle. Consideration of the curves of stress against rupture time at these temperatures (fig. 5) together with the actual amount of time the sample was in a given temperature interval (fig. 3), however, indicated that the rapid increase in strength of the alloy with decreasing temperature renders this total quantity negligibly small. Consequently, it was not considered in the calculations of the expected effects of overheating in the presence of stress. If slower cooling rates had been considered, this effect could have been substantial and in such a case should be included in the estimation of creep life expended by an overheat.

(6) While it is believed that the general trends of the effects of overheating will remain the same for other heat treatments of the alloys and for other heats, it seems quite probable that the magnitude of the effects could be quite different. More information is needed on this point.

(7) In view of metallurgical similarity, there is considerable temptation to assume that other alloys with Ti and Al as the major strengthening alloying elements would react to overheating in the same general way as M-252 alloy does. Before acceptance, however, this should be checked on other alloys, particularly those with wide variations in the other major alloying elements.

(8) The studies concerning the mechanism of the effects of overheating have been very superficial. The generalities of the findings for all three alloys considered will be doubtful until the mechanisms are understood. It seems, therefore, that this subject should receive considerable immediate attention.

CONCLUSIONS

The following results and conclusions were derived from an investigation of overheating M-252 alloy to temperatures of 1,650°, 1,800°, 1,900°, and 2,000° F during the course of rupture tests at 1,500° F:

1. Periodic 2-minute overheats to 1,900° or 2,000° F can very substantially increase rupture time of M-252 alloy at 1,500° F if repeated a sufficient number of times during the course of the test. Thus, for

such overheating to be damaging to rupture life at 1,500° F, a stress sufficiently high to use up a significant proportion of the total rupture life must be present during the overheats. Even a significant amount of creep damage can be offset during repeated overheating by the increase in rupture time from the temperature effect.

2. When M-252 alloy is overheated to 1,650° and 1,800° F in the absence of stress, the rupture life at 1,500° F is reduced. In the presence of stress, however, the damage is much less than would be anticipated due to some unidentified effect and there probably is a strengthening effect. Consequently, if stress is present, it must be high enough to use up a substantial amount of the rupture life if M-252 alloy is to be significantly damaged.

3. Heating to the overheat temperatures before testing cannot be used to evaluate the effects of repeated brief overheats during a test at 1,500° F because such treatments reduce strength at 1,500° F.

4. Estimation of the effect of overheats on creep-rupture properties at normal temperatures requires the experimental establishment of the effects of temperature. There does not appear to be a method of estimating this effect from commonly available data. Once this effect is established it can be added to the creep damage due to the presence of stress during the overheats to estimate the combined effect. The creep damage apparently can be closely approximated as a percentage of life used up from the ratio of the sum of the times of overheating to the total rupture time under the existing stress at the overheat temperature. The only exception to this conclusion found to date was for M-252 alloy overheated to 1,650° and 1,800° F when the damage was less than the computed value. This apparently resulted from a reversal of the effect of temperature as determined in the absence of stress due to the presence of stress during the overheats.

5. There was no significant effect of a few overheats on M-252 alloy to any of the temperatures considered due to the small change per overheat unless the stress was sufficiently high to use up a significant amount of the rupture life.

6. While overheating can increase the rupture life of M-252 alloy, it almost always reduced the rupture life of S-816 and HS-31 alloys at 1,500° F. Like M-252 alloy, overheating of S-816 and HS-31 alloy must be repeated a number of times to have a significant effect, unless a high stress is present, except for 2,000° F. These two alloys underwent a substantial loss in strength at 1,500° F from even one 2-minute overheat to 2,000° F.

7. Overheating in a turbine would have to be repeated a number of times or greatly prolonged beyond 2 minutes to alter significantly the

creep-rupture life at 1,500° F of parts made from M-252, S-816, or HS-31 alloys. The exceptions include the presence of a relatively high stress during overheating or overheating S-816 and HS-31 alloys to 2,000° F. With these exceptions, therefore, damage from a few brief overheats must arise from some other source, such as thermal shock or increased corrosion.

8. There are a number of fairly serious limitations on these conclusions imposed by the limited number of conditions of overheating studied, the absence of determination of effects of heat treatment conditions and heat-to-heat variations, and the uncertainty of the mechanism of the effects. In particular, the indication of improvement or lack of damage in M-252 alloy should not be accepted as characteristic of other alloys strengthened by titanium and aluminum without further proof.

9. The general qualitative effects established for M-252 alloy and those previously established for S-816 and HS-31 alloys are considered reliable. The magnitude of the effects quite probably varies with the metallurgical variables.

10. Several heats of M-252 alloy checked for this investigation were found to have quite different rupture strengths at 1,500° F. It was found that an anneal at 2,150° F prior to standard heat treatment considerably increased rupture strength of one heat at 1,500° F. Furthermore, a considerable difference in strength was found between material rolled from 2,150° F and the same material rolled from 1,950° F.

University of Michigan,
Ann Arbor, Mich., July 31, 1956.

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2. Rowe, J. P., and Freeman, J. W.: Effect of Overheating on Creep-Rupture Properties of HS-31 Alloy at 1,500° F. NACA TN 4083, 1957.
3. Miller, B. A., Winward, J. M., and Smith, W. K.: High-Heating-Rate Strength of Three Heat-Resistant Metals. NAVORD Rep. 2017, NOTS 670, Naval Ord. Lab., Mar. 16, 1953.
4. Simmons, Ward F., and Cross, Howard C.: The Elevated-Temperature Properties of Selected Super-Strength Alloys. Special Tech. Pub. No. 160, A.S.T.M., 1954.

TABLE I.- CHEMICAL COMPOSITION OF HEATS OF M-252 ALLOY

| Supplier and heat number | Composition, weight percent | | | | | | | | | | | |
|--|-----------------------------|------|------|-------|-------|-------|-------|-------|-------|------|------|------|
| | C | Mn | Si | S | P | Cr | Ni | Co | Mo | Ti | Al | Fe |
| Allegheny Ludlum Steel Corp., 43642 | 0.19 | 1.08 | 0.74 | ----- | ----- | 19.16 | 54.20 | 9.81 | 10.87 | 2.01 | 0.39 | 1.55 |
| Universal-Cyclops Steel Corp., A8133 | .13 | 1.30 | .60 | ----- | ----- | 20.00 | 52.12 | 10.70 | 9.92 | 2.65 | .90 | 1.68 |
| General Electric Co. vacuum melt, 837 | .16 | .82 | .60 | ----- | ----- | 18.70 | 54.15 | 9.70 | 10.00 | 2.71 | .96 | 2.20 |
| Universal-Cyclops Steel Corp. A-9586 | .16 | 1.19 | .80 | 0.004 | 0.014 | 18.73 | 54.03 | 10.26 | 9.58 | 2.62 | 1.05 | 1.56 |
| Haynes Stellite Co. vacuum melt, HT-28 | .12 | .10 | .35 | .007 | .002 | 19.22 | 54.38 | 9.73 | 10.18 | 2.40 | 1.12 | 2.40 |

TABLE II.- STRESS AND RUPTURE-TIME DATA FOR HEATS OF M-252 ALLOY

| Heat | Temperature, °F | Stress, psi | Rupture time, hr | Elongation, percent | Reduction of area, percent |
|--------|--------------------|----------------|---------------------|------------------------|-------------------------------|
| 43642 | 1,500 | 12,350 | 1,732 | 49 | 44 |
| | | 13,860 | 1,448 | 39 | 44 |
| | | 14,000 | 1,429 | 37 | 43 |
| | | | 1,385 | 37 | 38 |
| | | | 1,034 | 26 | 37 |
| | | | 1,121 | 28 | 30 |
| | | 14,360 | 636 | 44 | 43 |
| | | 15,410 | 606 | 52 | 44 |
| | | 16,950 | 456 | 51 | 47 |
| | | 18,460 | 279 | 45 | 54 |
| | | 19,470 | 245 | 63 | 53 |
| | | 20,490 | 193 | 55 | 54 |
| | | 21,530 | 155 | 46 | 52 |
| | 1,600 | 14,000 | 90 | 52 | 50 |
| | 1,800 | 14,000 | .25 | 92 | 98 |
| | 1,900 | 14,000 | .036 | 108 | 81 |
| A-8133 | 1,500 | 17,000 | 183 | 20 | 20 |
| | | 21,000 | 114 | 20 | 18 |
| | | 27,000 | 40 | 13 | 13 |
| 837 | 1,500 | 15,000 | 645 | 47 | 58 |
| | | 20,000 | 252 | 36 | 54 |
| | | 25,000 | 154 | 39 | 47 |
| | | 30,000 | 50 | 36 | 49 |
| | | | 62 | 38 | 48 |
| | | | 63 | 47 | 58 |
| | | 34,000 | 38 | 40 | 50 |
| A-9586 | 1,500 | 25,000 | 83 | 17 | 23 |
| | | 30,000 | 38 | (a) | 21 |
| | | | b34 | 22 | 27 |
| cHT-28 | 1,500 | 20,000 | 672 | 30 | 59 |
| | | 29,000 | 125 | 20 | 56 |
| | | 35,000 | 46 | 31 | 58 |
| | | | 45 | 51 | 60 |
| dHT-28 | 1,500 | 21,000 | 736 | 61 | 62 |
| | | 24,000 | 574 | 39 | 61 |
| | | | 450 | 46 | 55 |
| | | 26,500 | 356 | 36 | 59 |
| | | | 318 | 40 | 56 |
| | | 30,000 | 208 | 43 | 58 |
| | | 34,000 | 105 | 45 | 54 |
| | | | 82 | 49 | 58 |
| | | | 79 | 41 | 55 |
| | | 35,000 | 71 | 26 | 41 |
| | 1,650 | 24,000 | 9.2 | 46 | 64 |
| | | 30,000 | 2.9 | 43 | 64 |
| | 1,800 | 8,000 | 5.2 | 112 | 99 |
| | | 12,000 | e.63 | 97 | 99 |
| | | 24,000 | e.02 | 85 | 93 |
| | 1,900 | 4,000 | 34.3 | 78 | 99 |
| | 2,000 | 4,000 | 4.5 | 125 | 98 |

^aSpecimen damaged in removing from holders.

^bHeat A-9586 rolled at 2,150° F.

^cHeat HT-28 rolled at 1,950° F.

^dHeat HT-28 rolled at 2,150° F.

^eThis stress is above tensile strength at 1,800° F.

TABLE III

INFLUENCE OF MILL ANNEAL AND ROLLING TEMPERATURE ON
RUPTURE-TEST PROPERTIES OF M-252-ALLOY
STOCK FROM HEAT HT-28

[Test conditions: 1,500° F and 35,000-psi stress]

| Treatment | Rupture time, hr | Elongation, percent in 1 in. | Reduction of area, percent |
|---|---------------------|---------------------------------|----------------------------------|
| Rolled, heat-treated, and tested by Haynes Stellite Co.; heat treatment: Mill anneal 1 hr at 2,150° F, air-cooled plus 4 hr at 1,950° F, air-cooled plus aged 15 hr at 1,400° F | 138.0 | 39.0 | 44.2 |
| | 111.6 | 54.0 | 47.6 |
| Rolled and heat-treated by Haynes Stellite Co.; heat treatment: Mill anneal 1 hr at 2,150° F, air-cooled plus 4 hr at 1,950° F, air-cooled plus aged 15 hr at 1,400° F; samples tested by Univ. of Mich. | 163.7 | 30.0 | 42.0 |
| | 157.2 | 24.0 | 45.0 |
| Stock rerolled at Mich. from 1,950° F plus 4 hr at 1,950° F, air-cooled and aged 15 hr at 1,400° F, air-cooled | 46.0 | 31.0 | 35.0 |
| | 45.0 | 51.0 | 37.0 |
| Stock rerolled at Mich. from 1,950° F plus mill anneal 1 hr at 2,150° F, air-cooled plus 4 hr at 1,950° F, air-cooled, and aged 15 hr at 1,400° F, air-cooled | 161.6 | 41.0 | 40.0 |
| Stock rerolled at Mich. from 2,150° F plus 4 hr at 1,950° F, air-cooled and aged 15 hr at 1,400° F, air-cooled | 71.0 | 26.0 | 24.0 |

TABLE IV

CYCLIC OVERHEATS IN ABSENCE OF
STRESS FOR M-252 ALLOY

[Each overheat was for 2 min]

| Heat | Overheat temp., °F | Number of overheats | Rupture time | | Elongation, percent | Reduction of area, percent | |
|---|--|------------------------|--------------|---------|------------------------|-------------------------------|----|
| | | | Hr | Percent | | | |
| 485-hr rupture stress of 24,000 psi; overheats every 12 hr | | | | | | | |
| ^a HT-28 | ^b 1,500 | 31 | 382 | 79 | 43 | 62 | |
| | | 16 | 243 | 50 | 42 | 64 | |
| | | 8 | 466 | 96 | 41 | 59 | |
| | 1,800 | 42 | 549 | 113 | 15 | 53 | |
| | | 20 | 391 | 81 | 50 | 62 | |
| | | 20 | 283 | 58 | 25 | 51 | |
| | 1,900 | 64 | 871 | 179 | 13 | 50 | |
| | | 29 | 747 | 154 | 33 | 59 | |
| | 2,000 | 60 | 927 | 191 | 33 | 58 | |
| | | 30 | 705 | 145 | 40 | 61 | |
| | 80-hr rupture stress of 34,000 psi; overheats every 5 hr | | | | | | |
| | ^a HT-28 | 1,650 | 18 | 85 | 106 | 37 | 49 |
| 11 | | | 55 | 69 | 34 | 42 | |
| 7 | | | 51 | 64 | 28 | 44 | |
| 1,800 | | 10 | 53 | 66 | 22 | 27 | |
| | | 9 | 48 | 60 | 25 | 37 | |
| | | 5 | 68 | 85 | 38 | 52 | |
| 1,900 | | 30 | 182 | 227 | 23 | 45 | |
| | | 15 | 137 | 172 | 35 | 53 | |
| 2,000 | | 30 | 211 | 263 | 16 | 50 | |
| | | 15 | 171 | 214 | 25 | 46 | |
| 1200-hr rupture stress of 14,000 psi; overheats every 12 hr | | | | | | | |
| 43642 | | ^b 1,500 | 72 | 863 | 72 | 30 | 36 |
| | 1,900 | 98 | 1,172 | 98 | 25 | 28 | |
| 115-hr rupture stress of 24,000 psi; overheats every 5 hr | | | | | | | |
| 837 | 1,900 | 36 | 182 | 158 | 32 | 38 | |

^aHeat HT-28 rolled from 2,150° F.

^bLoad cycled at 1,500° F.

TABLE V

TESTS OF PREHEATED SPECIMENS OF M-252 ALLOY

| Heat | Preheat conditions | | Rupture time | | Elongation, percent | Reduction of area, percent |
|---|--------------------|--------------|--------------|---------|------------------------|-------------------------------|
| | Temp., °F | Time, min | Hr | Percent | | |
| Tests run at 34,000 psi; rupture time, 80 hr | | | | | | |
| HT-28 | 1,650 | 20 | 70 | 87 | 45 | 55 |
| | 1,900 | 60 | 62 | 78 | 50 | 56 |
| | 2,000 | 60 | 63 | 79 | 38 | 42 |
| Tests run at 14,000 psi; rupture time, 1,200 hr | | | | | | |
| 43642 | 1,600 | 240 | 869 | 72 | 40 | 43 |
| | | 240 | 1,232 | 103 | 32 | 46 |

TABLE VI

OVERHEATS UNDER LOAD FOR M-252 ALLOY

| Heat | Overheat conditions | | No. of cycles | Rupture time, hr | Elongation, percent | Reduction of area, percent |
|---|--|-------------|------------------|------------------|---------------------|----------------------------|
| | Temp., °F | Stress, psi | | | | |
| All tests run under 24,000 psi at 1,500° F with 2-min overheat cycles every 12 hr | | | | | | |
| ^a HT-28 | 1,650 | 24,000 | 30 | 392 | 34 | 57 |
| | | 30,000 | 25 | 380 | 31 | 54 |
| | 1,800 | 8,000 | 39 | 590 | 31 | 54 |
| | | 10,000 | 30 | 462 | 50 | 57 |
| | 1,900 | 5,000 | 50 | 749 | 37 | 56 |
| | 2,000 | 4,000 | 33 | 603 | 32 | 49 |
| | All tests run under 14,000 psi at 1,500° F with overheat cycles as indicated | | | | | |
| | 43642 | 1,600 | 14,000 | ^b 1 | 673 | 31 |
| 14,000 | | | ^c 1 | 1,043 | 38 | 49 |
| 14,000 | | | ^d 1 | 1,286 | 49 | 45 |
| 1,800 | | 14,000 | ^e 4 | 25.2 | 31 | 78 |
| 1,900 | | 14,000 | ^e 1.1 | 10.0 | 37 | 80 |

^aHeat HT-28 rolled at 2,150° F.

^bSingle 2-hr cycle delayed to 404 hr.

^cSingle 2-hr cycle delayed to 142 hr.

^dSingle 2-hr cycle delayed to 456 hr.

^eTest cycled every 5 hr.

TABLE VII

CALCULATION OF THEORETICAL AND PREDICTED RUPTURE TIMES
FOR TESTS ON SPECIMENS OF M-252 ALLOY
OVERHEATED IN PRESENCE OF STRESS

| Overheat conditions | | | Theoretical values for maximum no. of overheats possible | | | | | | Values predicted from actual test conditions | | | | | Average calculated rupture time, hr | Actual rupture time, hr | Apparent $f_t - f_s$ |
|---------------------|---------------|----------------------------------|---|---------------------|------------------|---------------------|------------------|---------------------|---|---------------------------------|--------------|--------------|--------------------|--|----------------------------------|-------------------------|
| Temp., °F | Stress psi | Normal rupture time, hr | Minimum strength | | Average strength | | Maximum strength | | No. of cycles | Time to attain cycles, hr | f_t (a) | f_s (a) | $f_t - f_s$ (a) | | | |
| | | | No. of cycles | Rupture time, hr | No. of cycles | Rupture time, hr | No. of cycles | Rupture time, hr | | | | | | | | |
| 1,650 | 24,000 | 9.2 | 20 | 230 | 23 | 270 | 27 | 310 | 30 | (b) | (b) | (b) | (b) | | 392 | 0.81 |
| | 30,000 | 2.9 | 17 | 190 | 20 | 230 | 22 | 255 | 25 | | | | | | 380 | .78 |
| 1,800 | 8,000 | 5.2 | 19 | 220 | 22 | 255 | 25 | 285 | 39 | (b) | (b) | (b) | (b) | | 590 | 1.22 |
| | 10,000 | 1.6 | 15 | 165 | 17 | 190 | 18 | 205 | 30 | | | | | | 462 | .97 |
| 1,900 | 5,000 | 9.0 | 49 | 360 | 70 | 815 | 93 | 1,085 | 50 | 590 | 1.75 | 0.19 | 1.54 | 747 | 749 | 1.55 |
| 2,000 | 4,000 | 4.5 | 42 | 480 | 57 | 665 | 76 | 885 | 33 | 385 | 1.52 | .24 | 1.28 | 620 | 603 | 1.24 |
| 1,600 | 14,000 | 90 | (c) | (c) | (c) | (c) | (c) | (c) | 1(2 hr) | --- | 1.00 | .02 | .98 | 1,175 | 673 1,043 1,286 | .56 .87 1.07 |
| 1,800 | 14,000 | .25 | (d) | (d) | (d) | (d) | (d) | (d) | 4 | 20 | .90 | .53 | .37 | 444 | 25.2 | .02 |
| 1,900 | 14,000 | .036 | (d) | (d) | (d) | (d) | (d) | (d) | 1.1 | 10 | 1.02 | 1.02 | 0 | 0 | 10 | 0 |

^a f_t , rupture time for overheating with stress removed divided by normal rupture time at 1,500° F; f_s , time at overheat temperature under stress divided by normal rupture time at overheat temperature under stress.

^b Calculation not possible since actual number of cycles exceeded theoretical maximum number possible.

^c Not calculated since cyclic overheating was not done for these tests.

^d Negligible value.

^e This calculation predicts that all of available rupture life at 1,900° F would be used up at end of 2.2 min of overheating. Since 10 hr elapse before this amount of time is accumulated, this indicates good agreement.



L-57-4145

Figure 1.- Photograph showing creep-rupture unit modified for use in overheating by resistance heating.

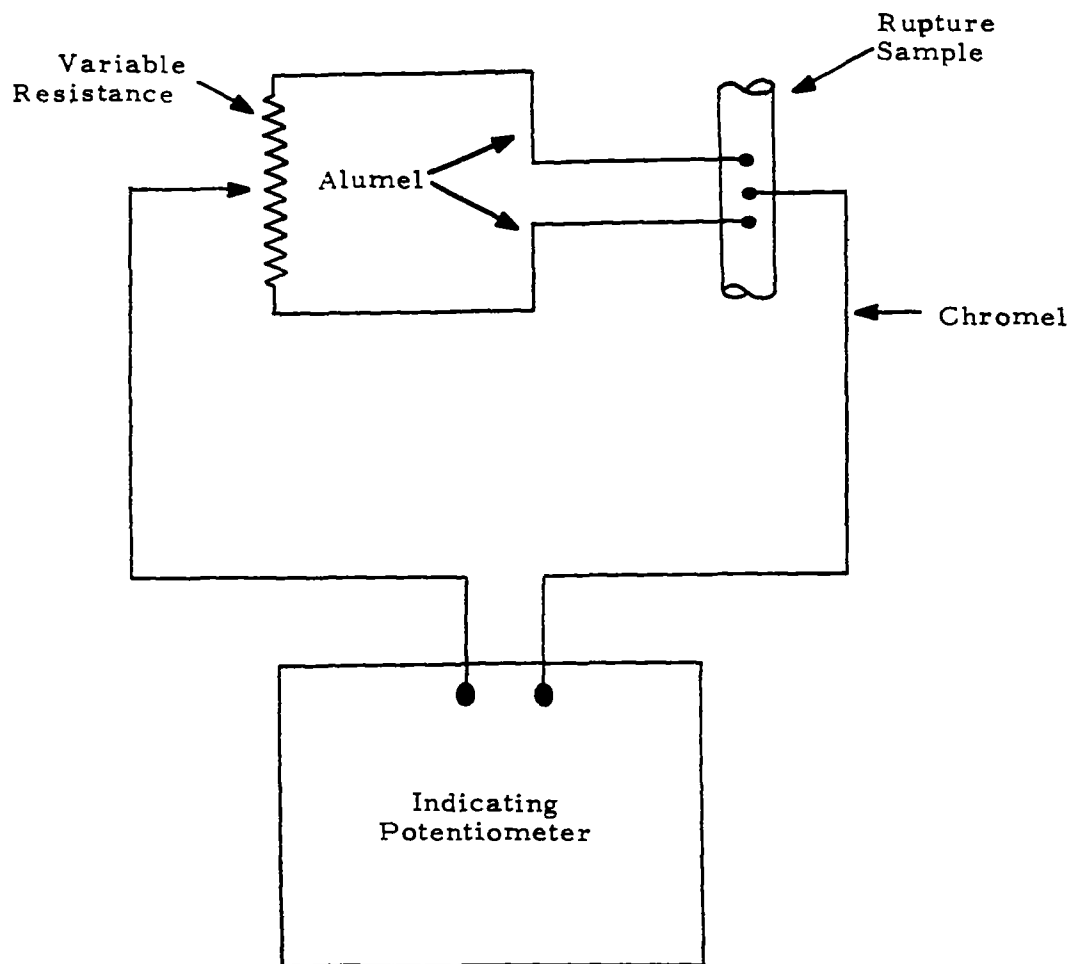


Figure 2.- Schematic wiring diagram of system used for measurement of temperature during overheats to avoid extraneous electromotive force from heating current.

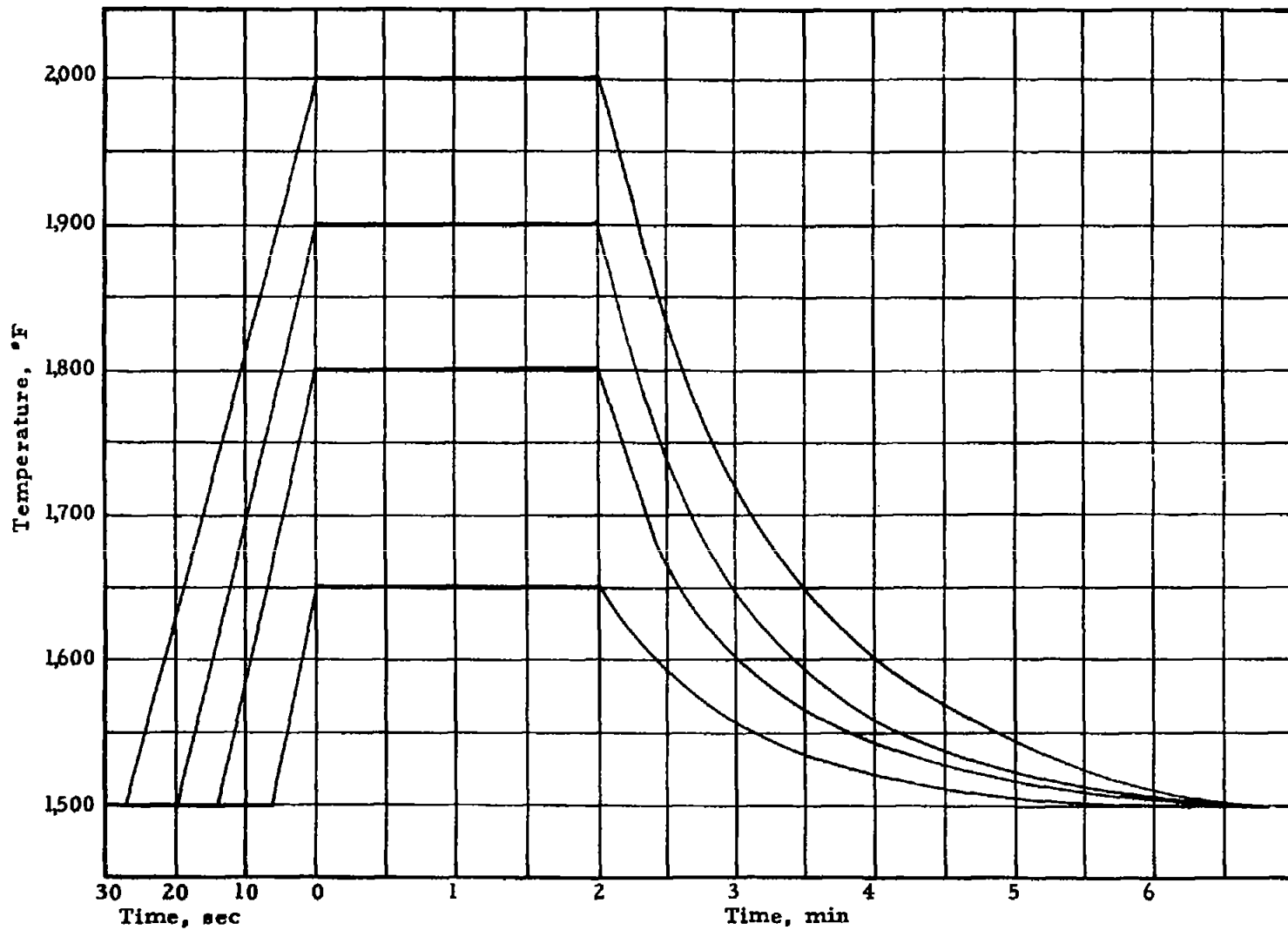


Figure 3.- Typical time-temperature curves for overheats to each of temperatures employed.

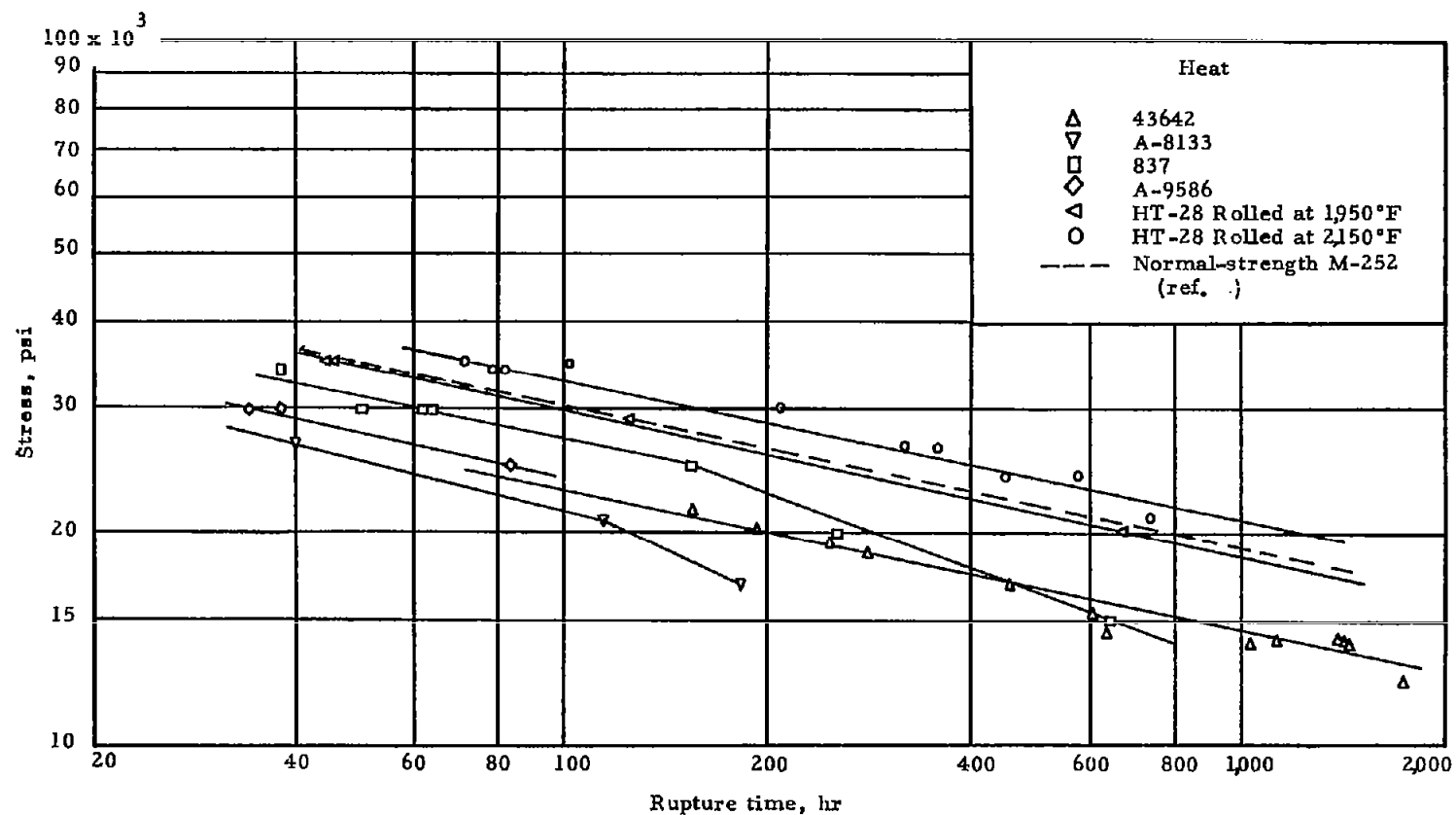
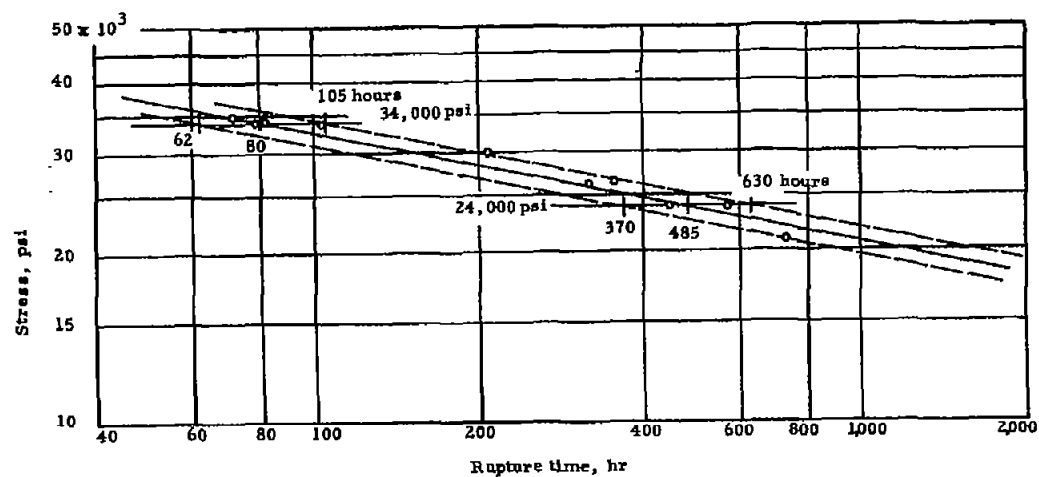
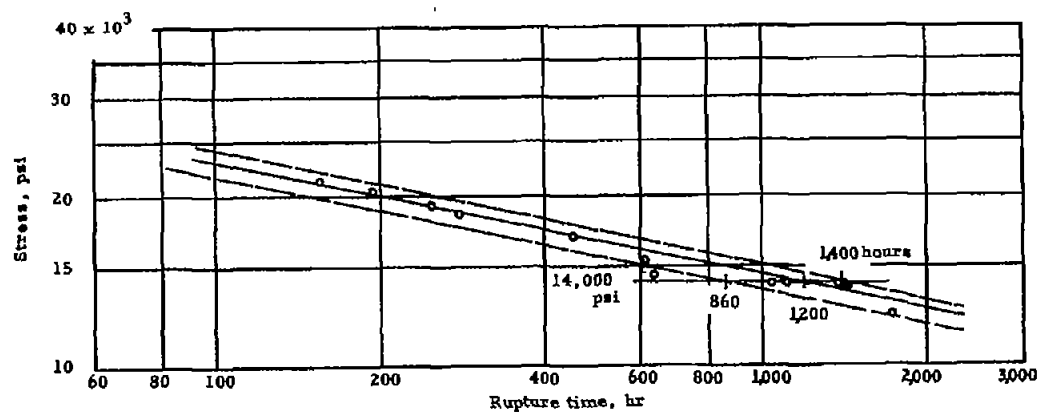


Figure 4.- Curves of stress against rupture time at 1,500° F for five heats of M-252 alloy used in present investigation.



(a) Heat HT-28.



(b) Heat 43642.

Figure 5.- Curves of stress against rupture time at 1,500° F for M-252 alloy showing ranges in rupture times predicted by available test data for two heats of material used for overheating.

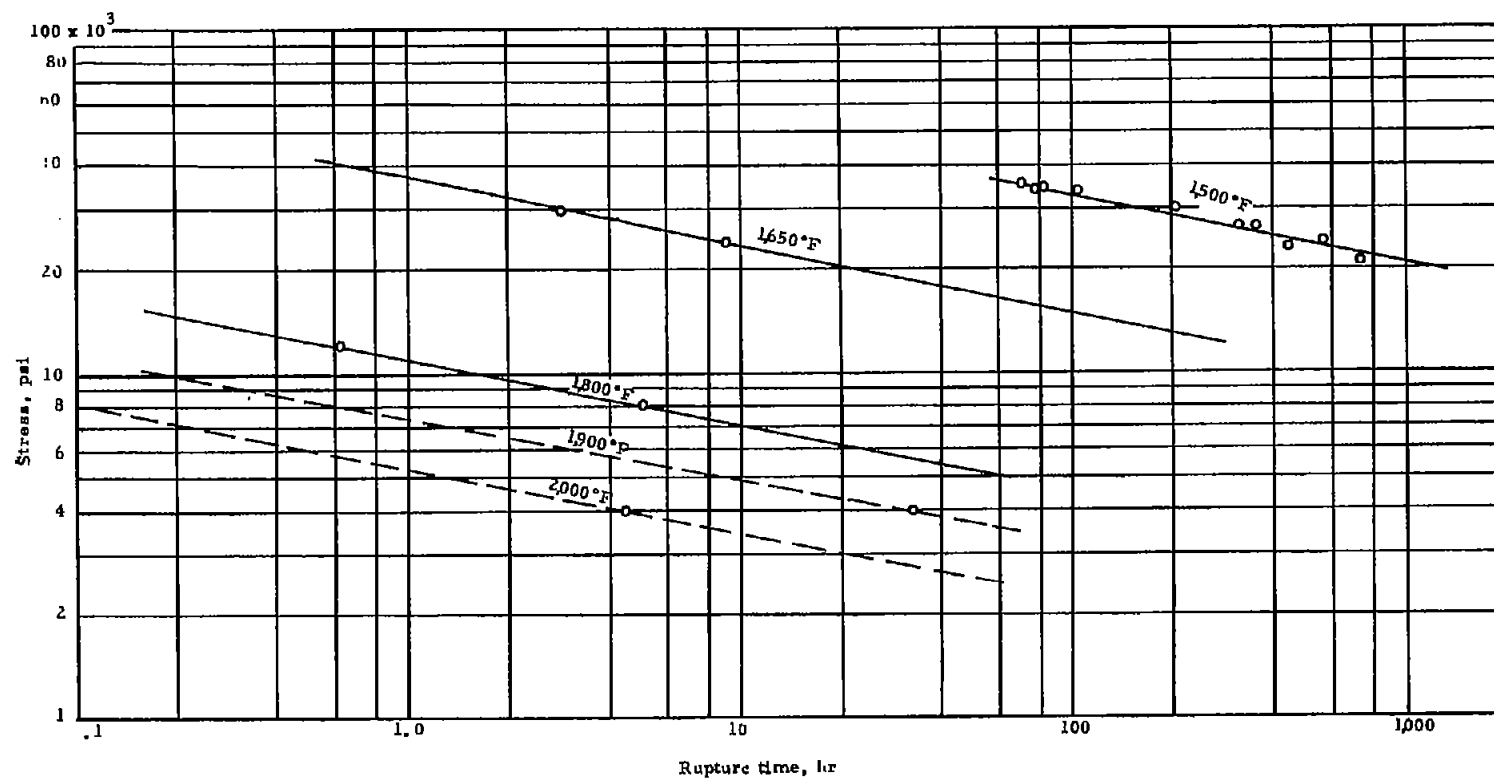
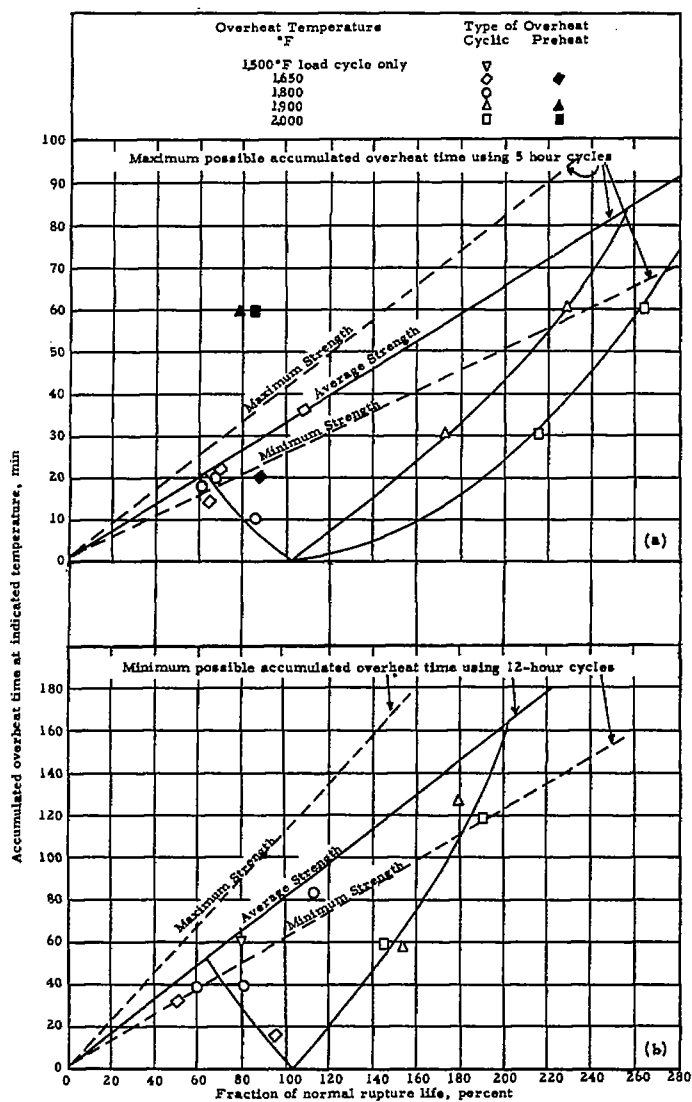


Figure 6.- Curves of stress against rupture time at 1,500°, 1,650°, 1,800°, 1,900°, and 2,000° F for heat HT-28 of M-252 alloy rolled at 2,150° F.



(a) Tests at 1,500° F and 34,000 psi (normal rupture time, 80 hours); overheats every 5 hours.

(b) Tests at 1,500° F and 24,000 psi (normal rupture time, 485 hours); overheats every 12 hours.

Figure 7.- Effect on heat HT-28 of M-252 alloy of amount of overheating to 1,650°, 1,800°, 1,900°, and 2,000° F on rupture life under a stress of 24,000 or 34,000 psi. Tests with cyclic 2-minute overheats every 5 or 12 hours with stress removed during overheat period.

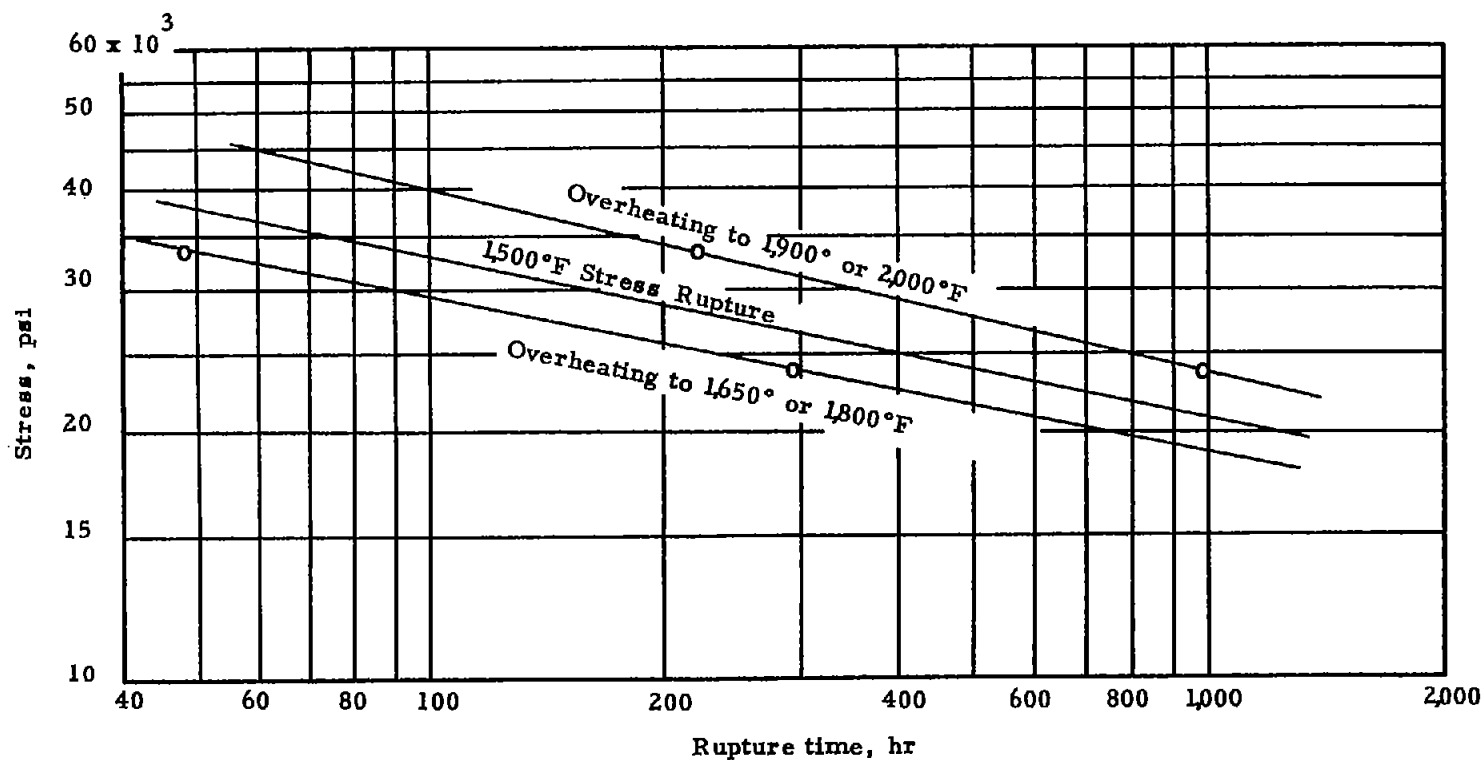
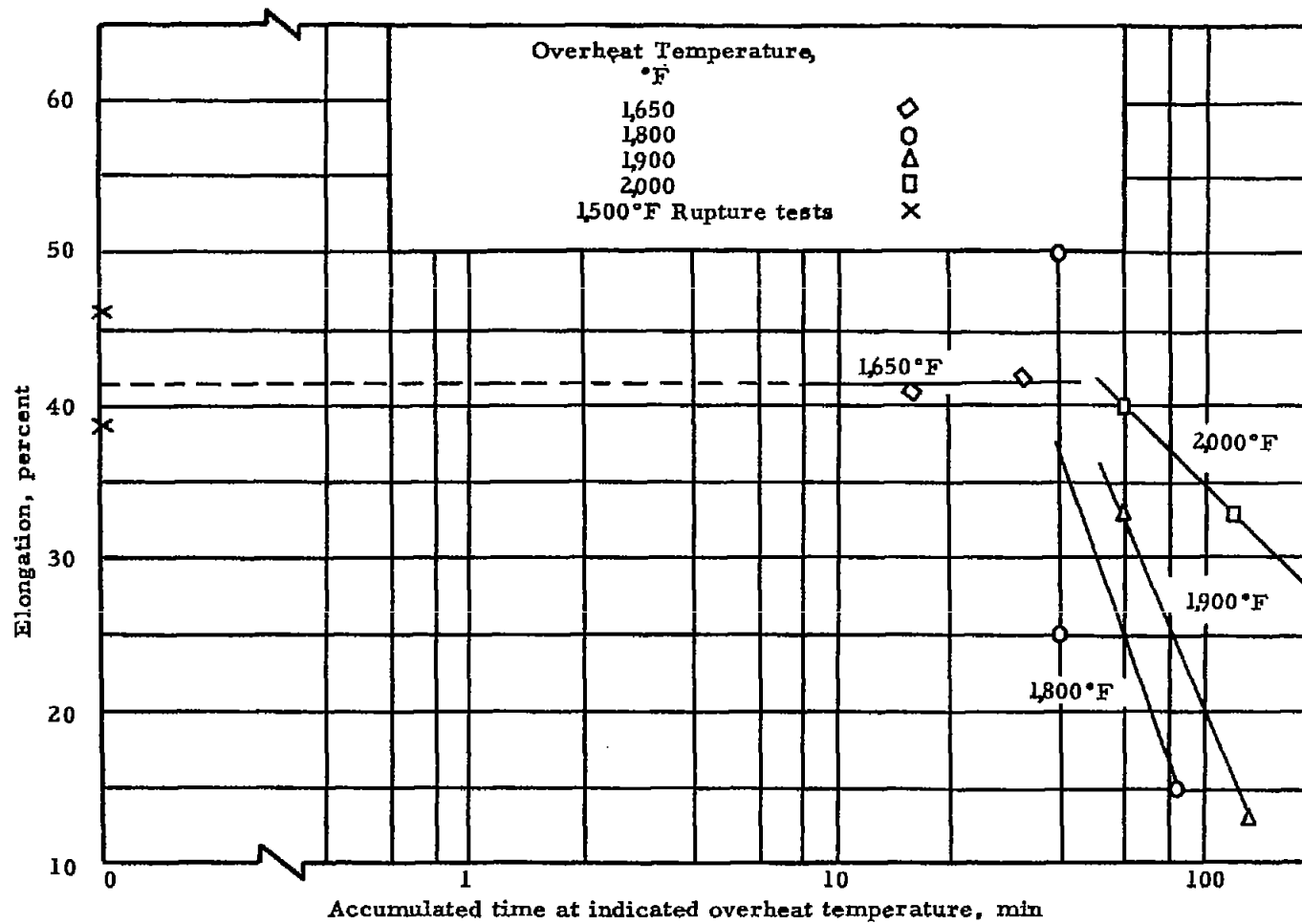
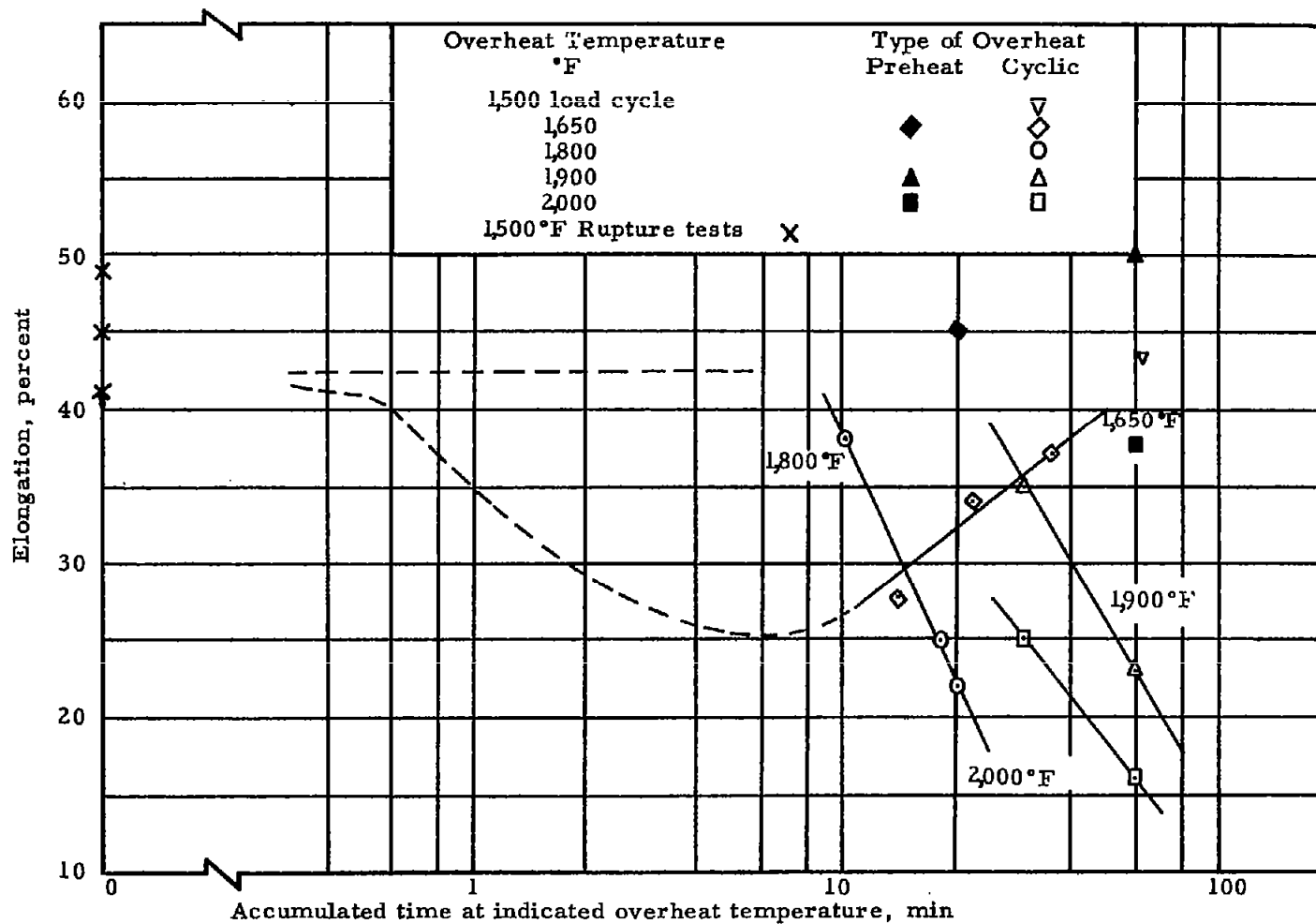


Figure 8.- Comparative curves of stress against rupture time for M-252 alloy (heat HT-28 rolled at 2,150° F) showing average extrapolated maximum effects of overheating to 1,650° and 1,800° F or to 1,900° and 2,000° F in absence of stress.



(a) 24,000-psi stress. Tests received one 2-minute overheat every 12 hours in absence of stress.

Figure 9.- Effect of time at indicated temperature on elongation at rupture under 1,500° F and 24,000 and 34,000 psi.



(b) 34,000-psi stress. Cyclic tests received one 2-minute overheat every 5 hours in absence of stress.

Figure 9.- Concluded.

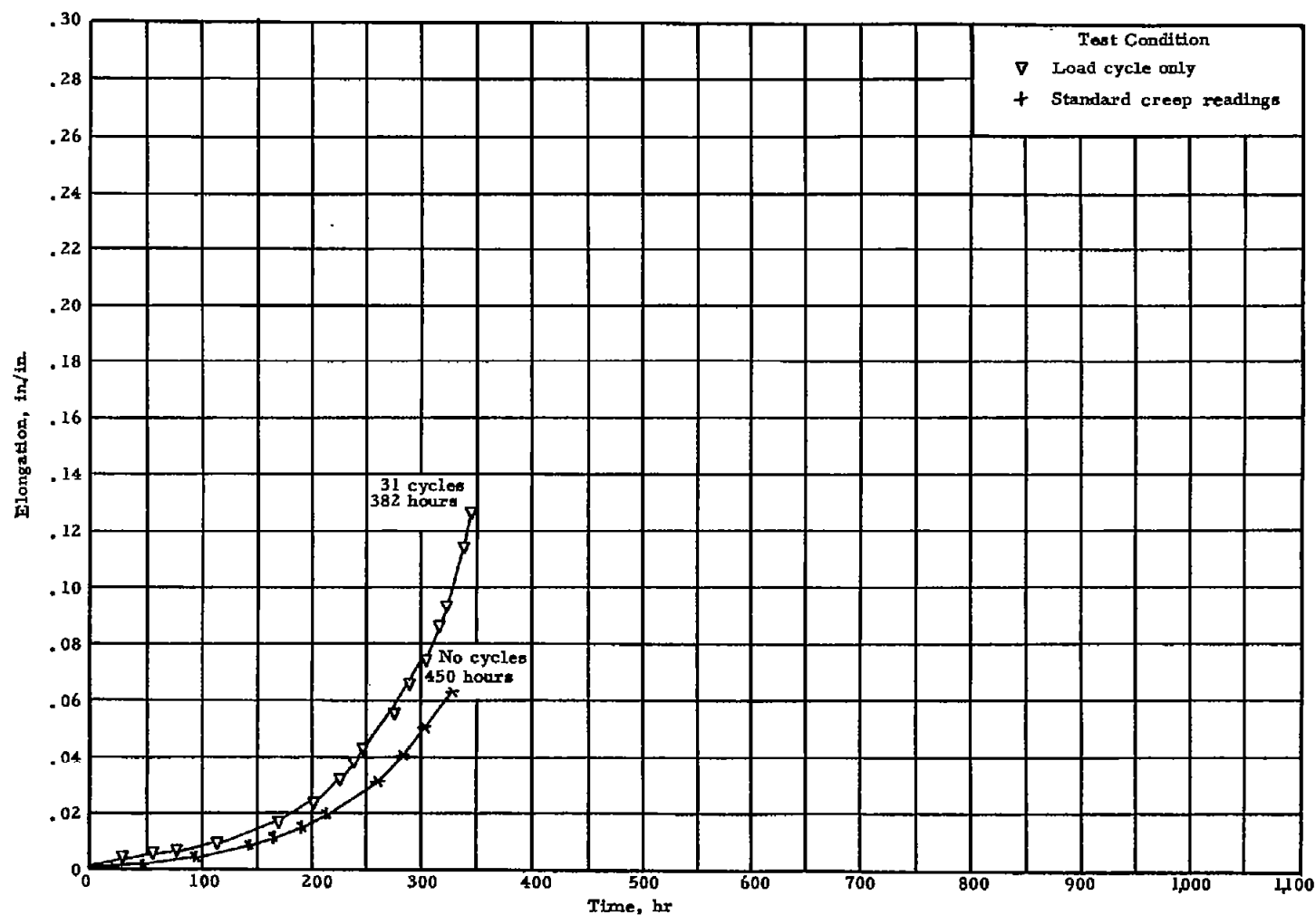
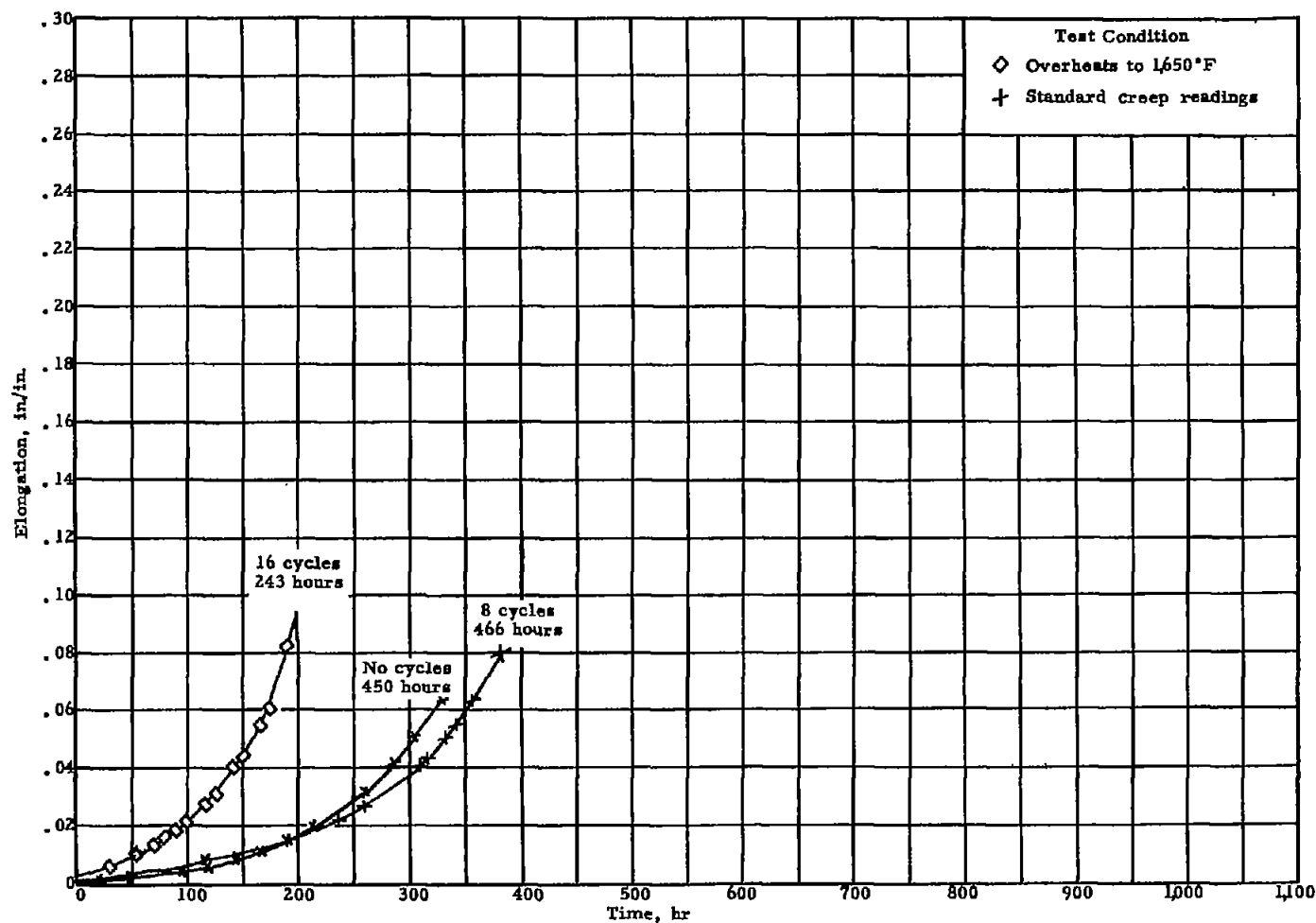
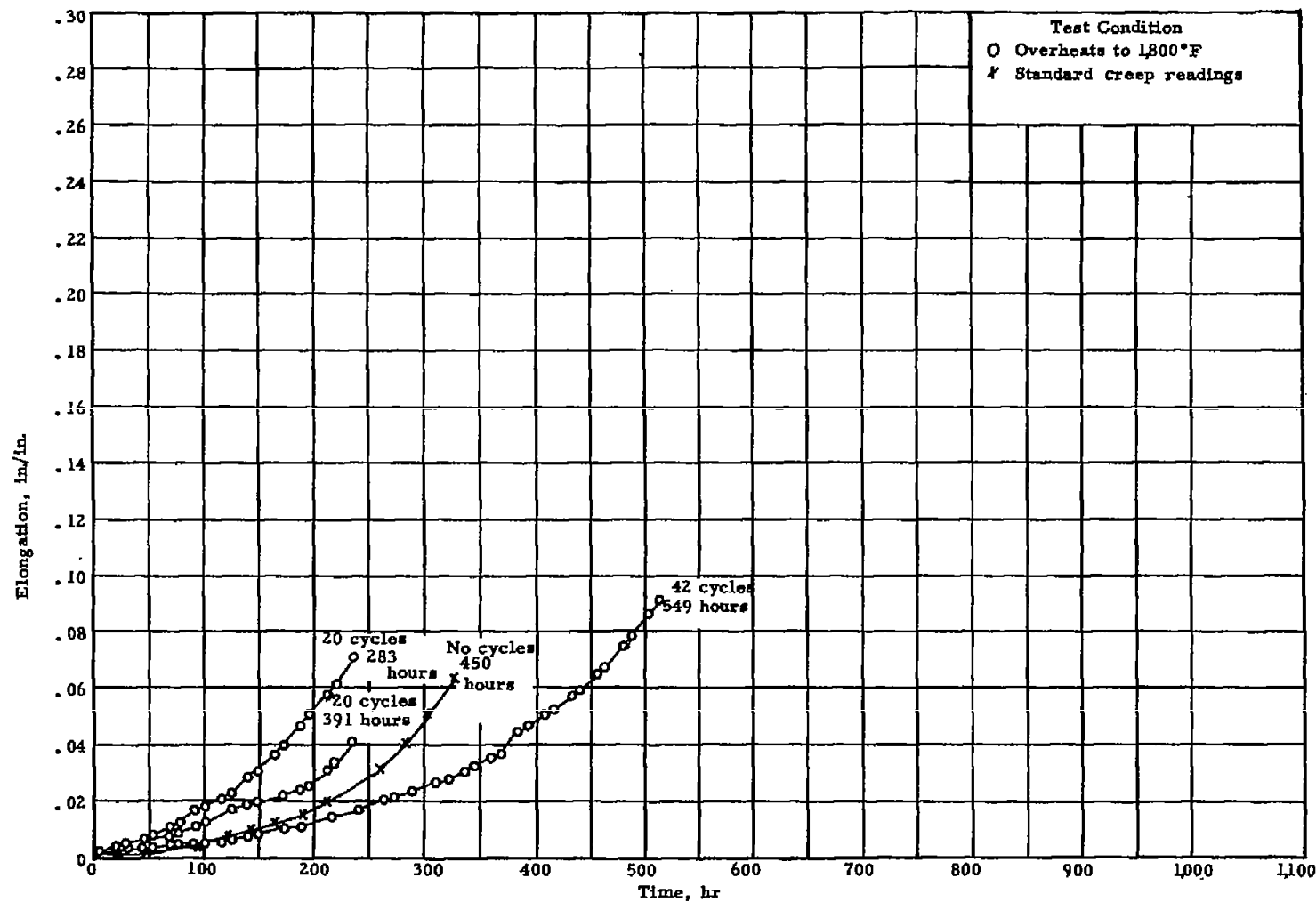


Figure 10.- Comparative creep curves at 1,500° F and 24,000 psi for heat HT-28 for cyclic removal of stress every 12 hours until rupture. Numbers indicate rupture time and number of cycles.



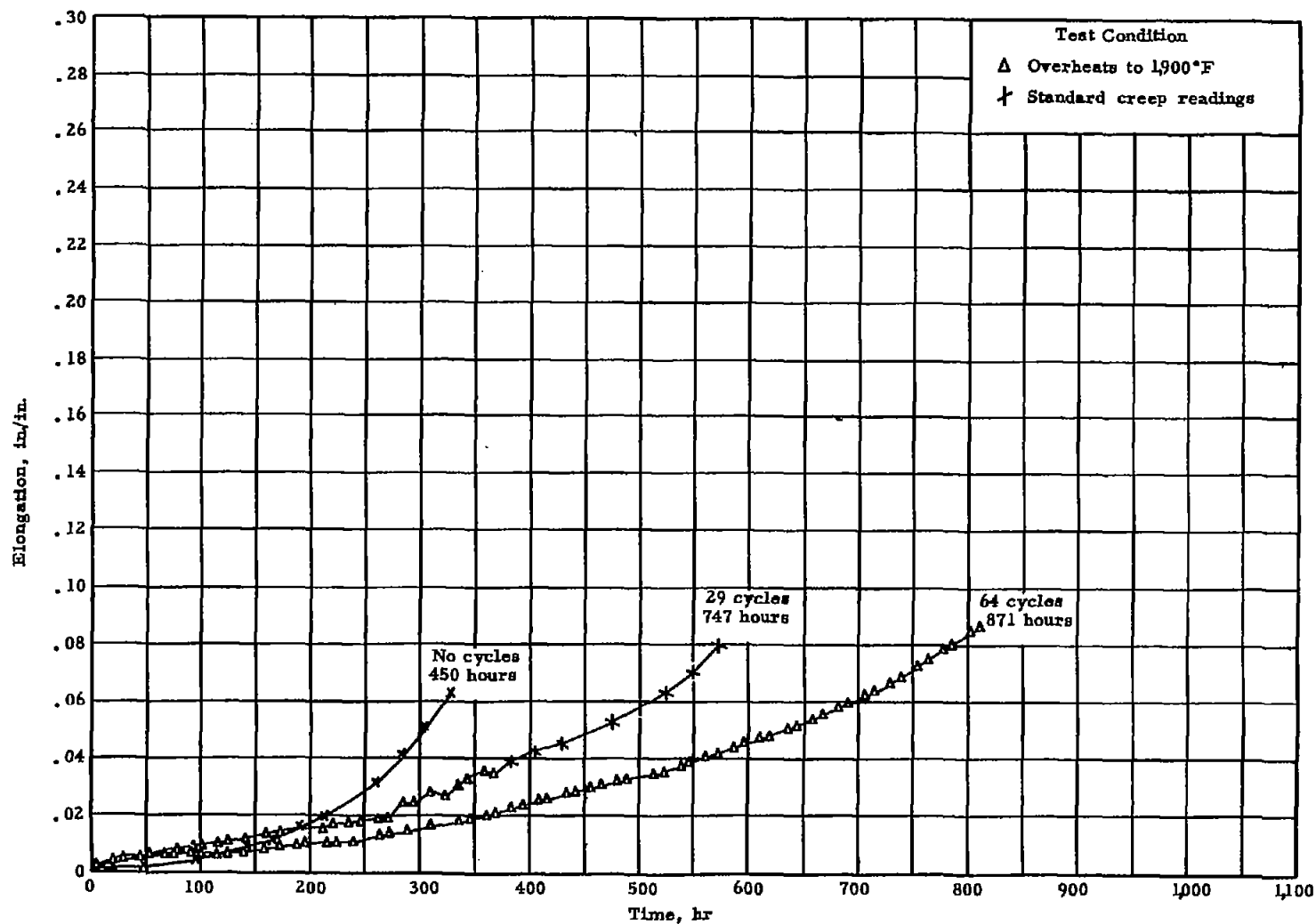
(a) 24,000-psi stress; overheats to 1,650° F every 12 hours.

Figure 11.- Comparative creep curves at 1,500° F and 24,000 and 34,000 psi for heat HT-28 overheated to various temperatures every 5 or 12 hours in absence of stress. Numbers indicate rupture time and number of cycles.



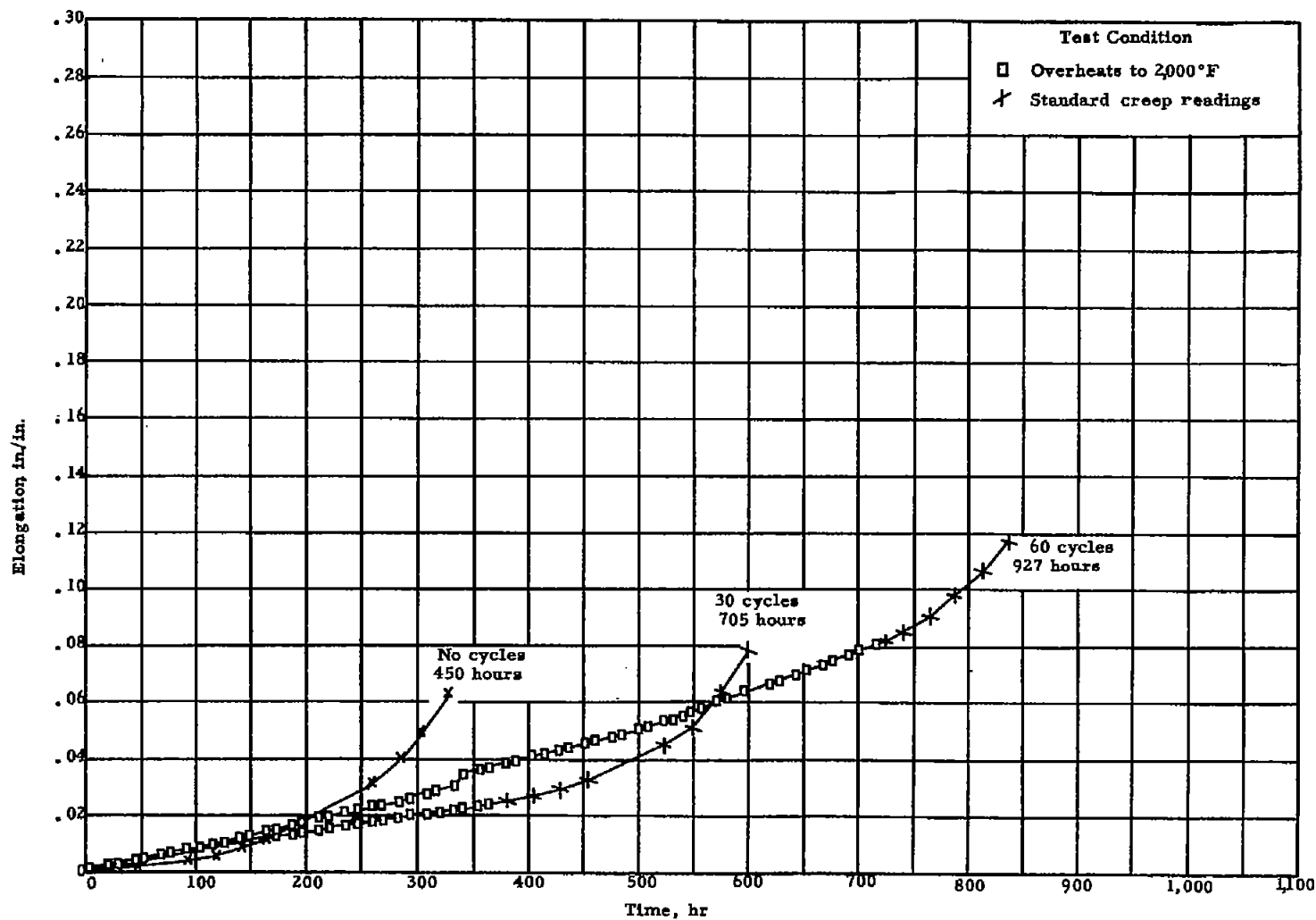
(b) 24,000-psi stress; overheats to 1,800° F every 12 hours.

Figure 11.- Continued.



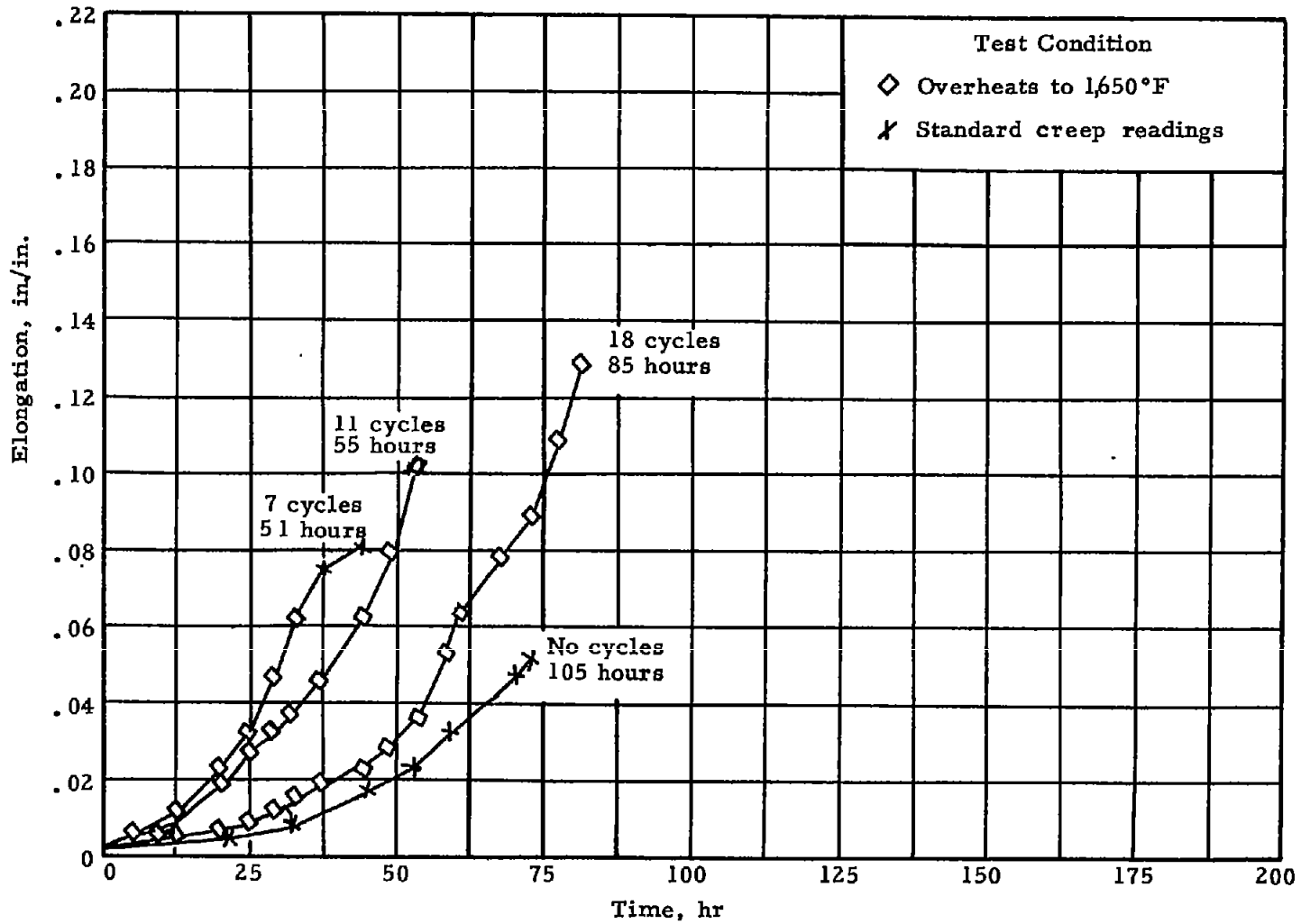
(c) 24,000-psi stress; overheats to 1,900° F every 12 hours.

Figure 11.- Continued.



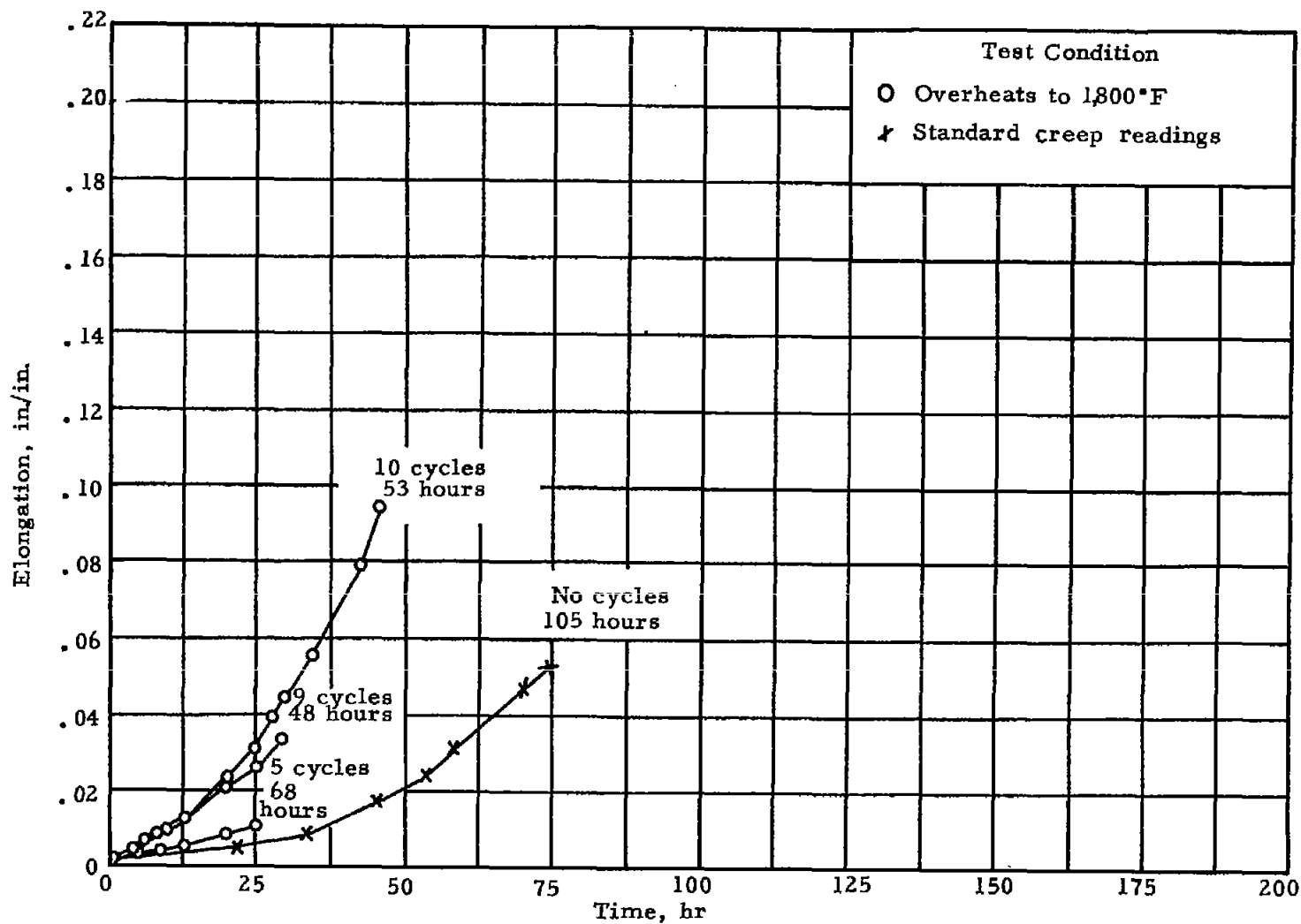
(d) 24,000-psi stress; overheats to 2,000° F every 12 hours.

Figure 11.- Continued.



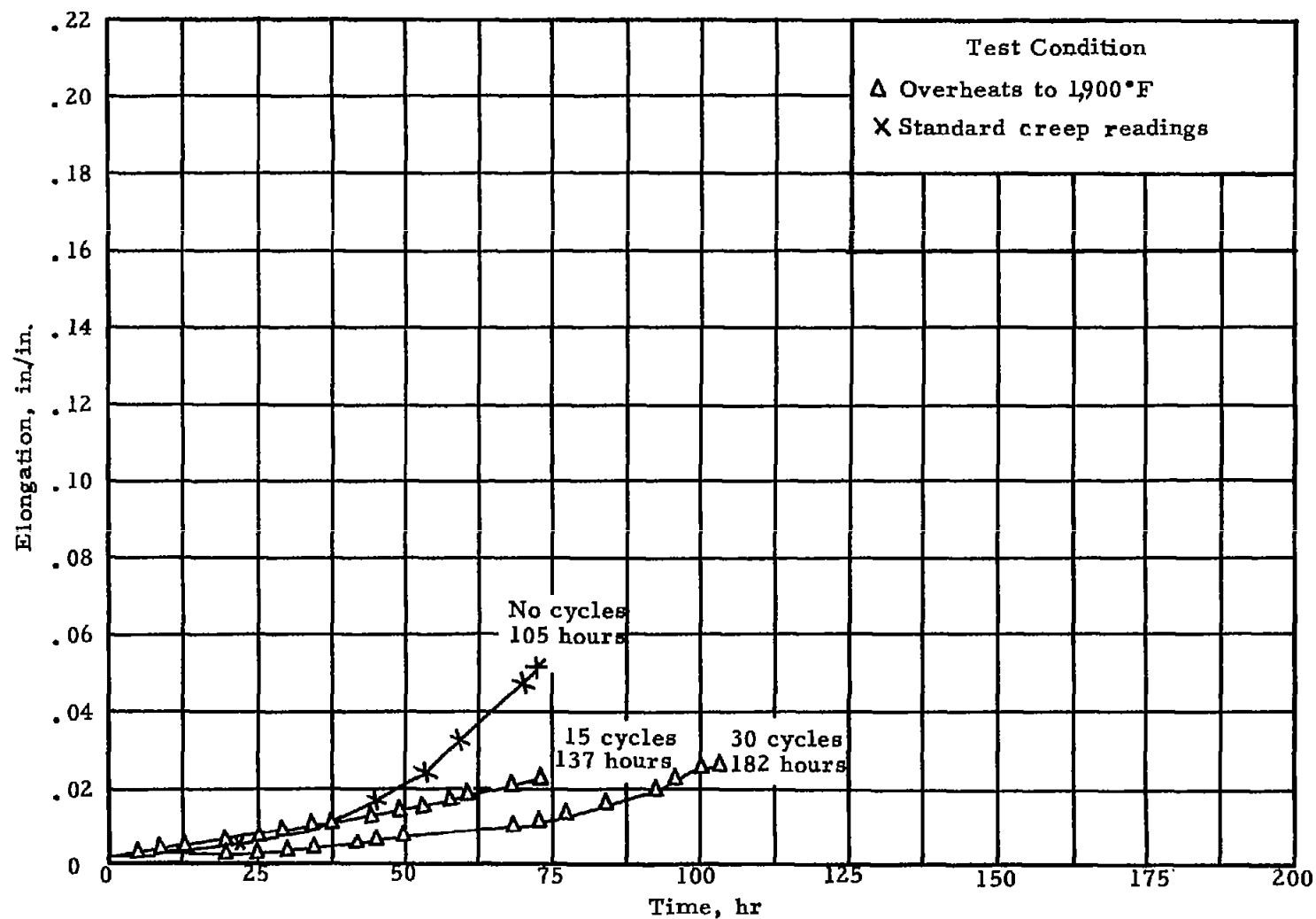
(e) 34,000-psi stress; overheats to 1,650° F every 5 hours.

Figure 11.- Continued.



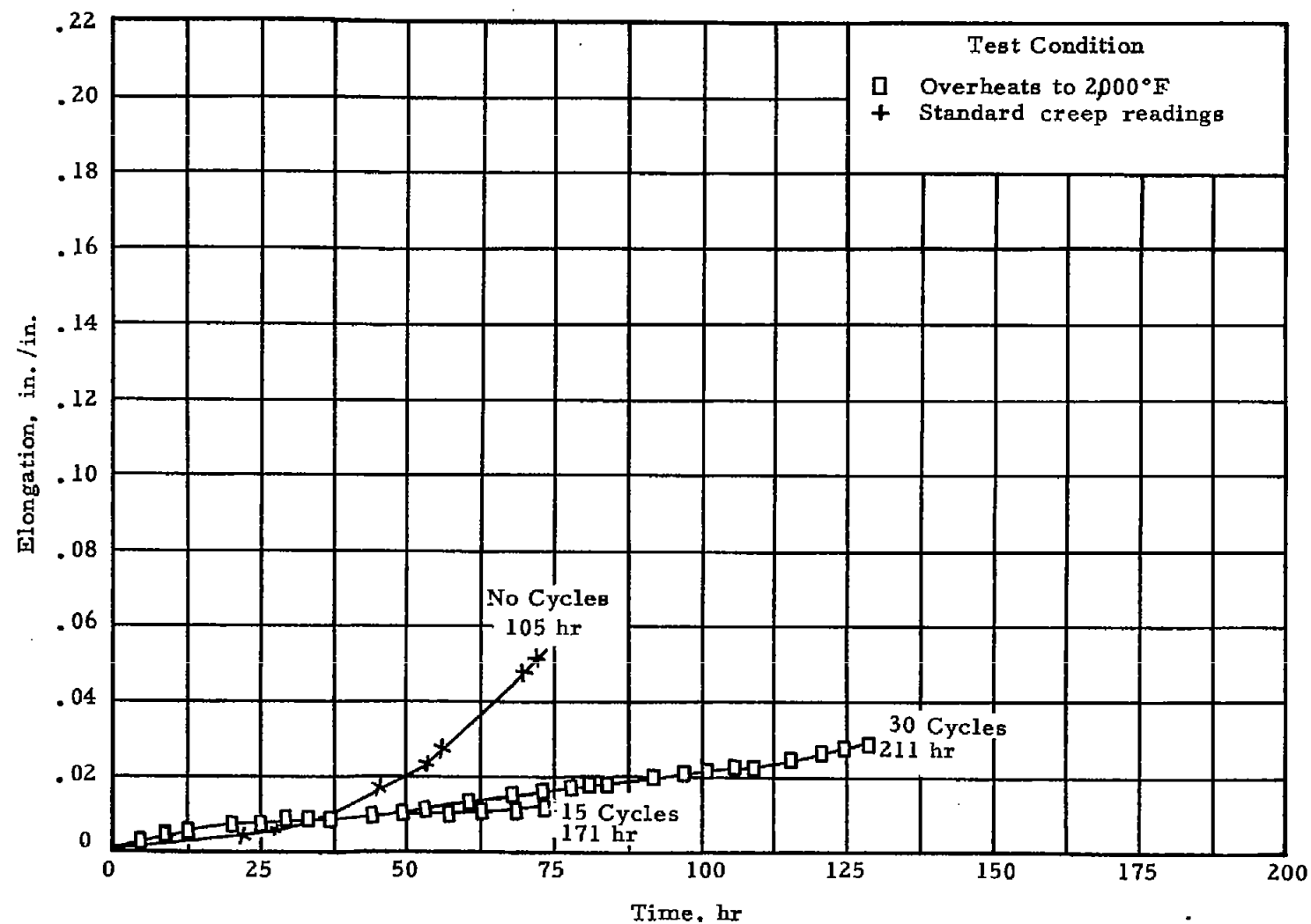
(f) 34,000-psi stress; overheats to 1,800° F every 5 hours.

Figure 11.- Continued.



(g) 34,000-psi stress; overheats to 1,900° F every 5 hours.

Figure 11.- Continued.



(h) 34,000-psi stress; overheats to 2,000° F every 5 hours.

Figure 11.- Concluded.

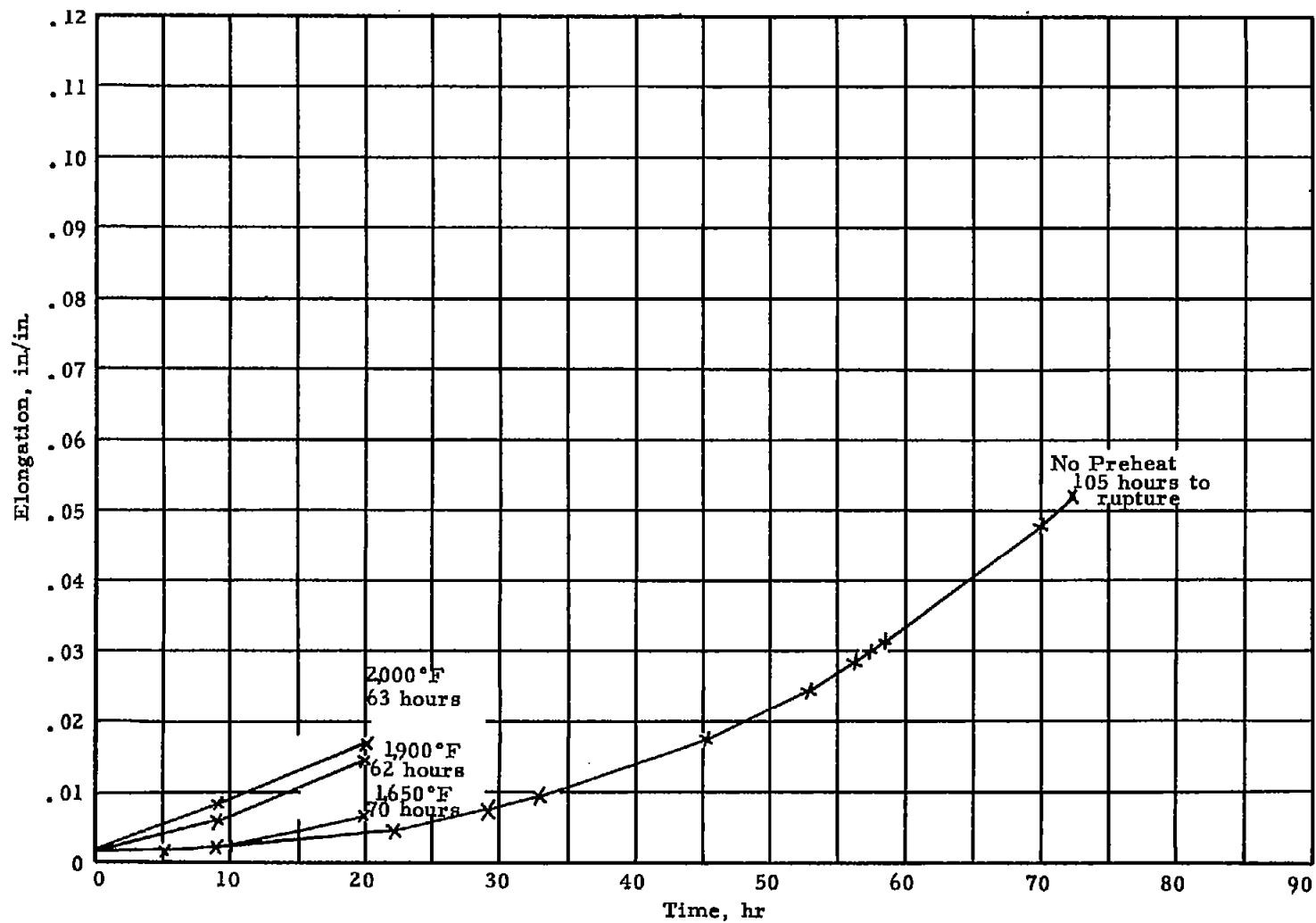


Figure 12.- Comparative creep curves at 1,500° F and 34,000 psi for tests preheated to indicated temperatures.

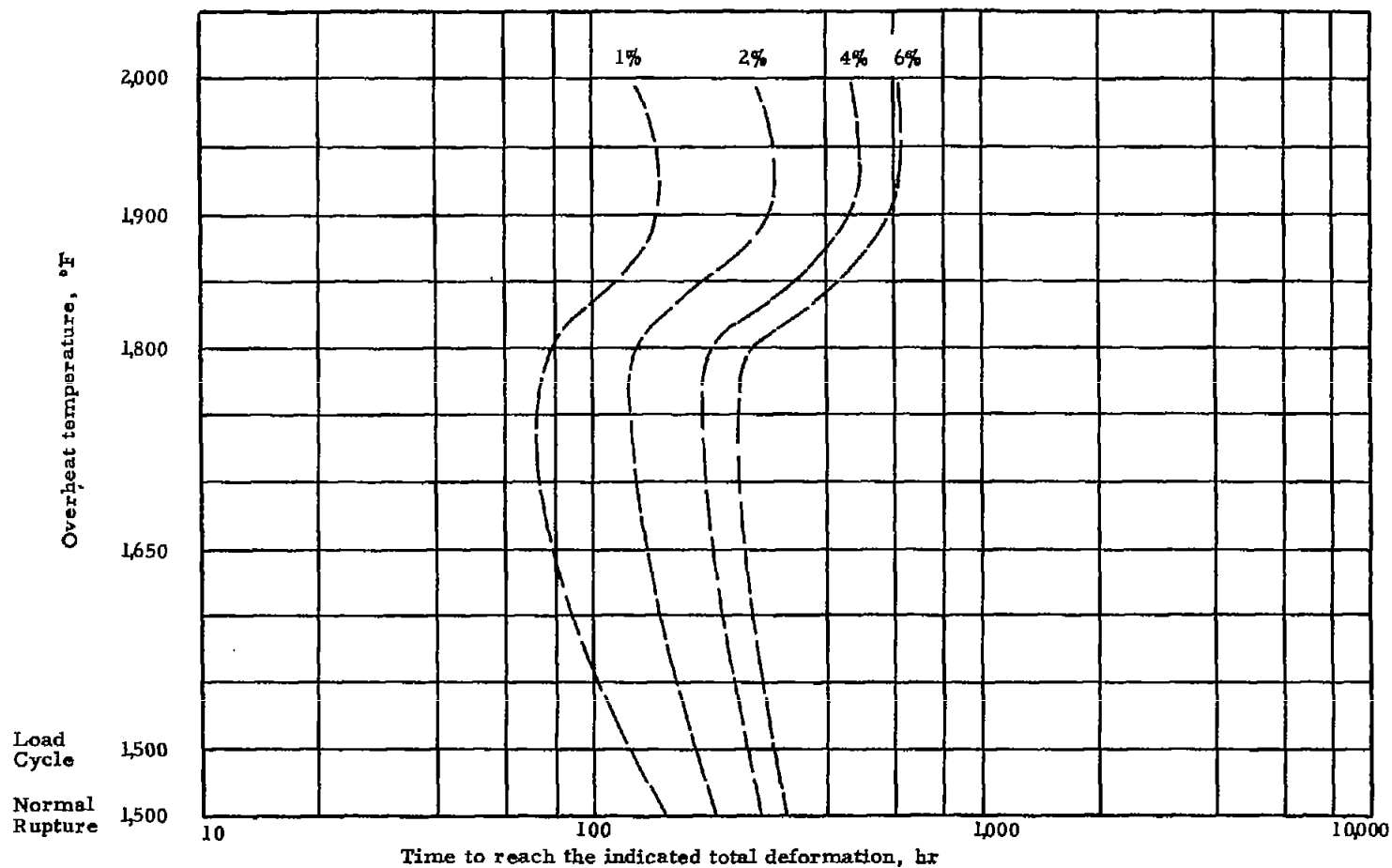


Figure 13.- Influence of temperature of continued cyclic overheating in absence of stress on time to reach indicated total deformation for tests at 1,500° F and 24,000 psi.

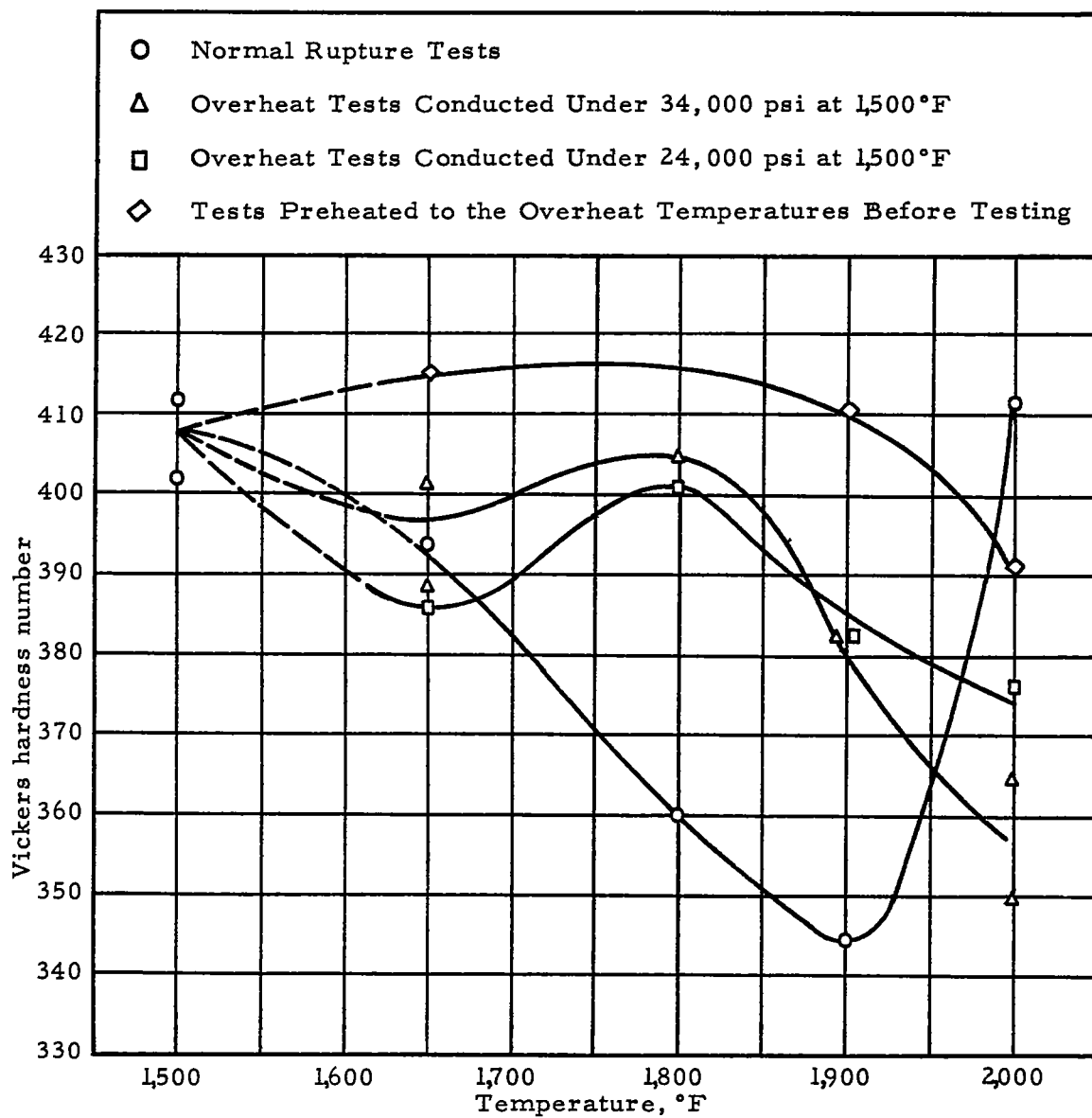
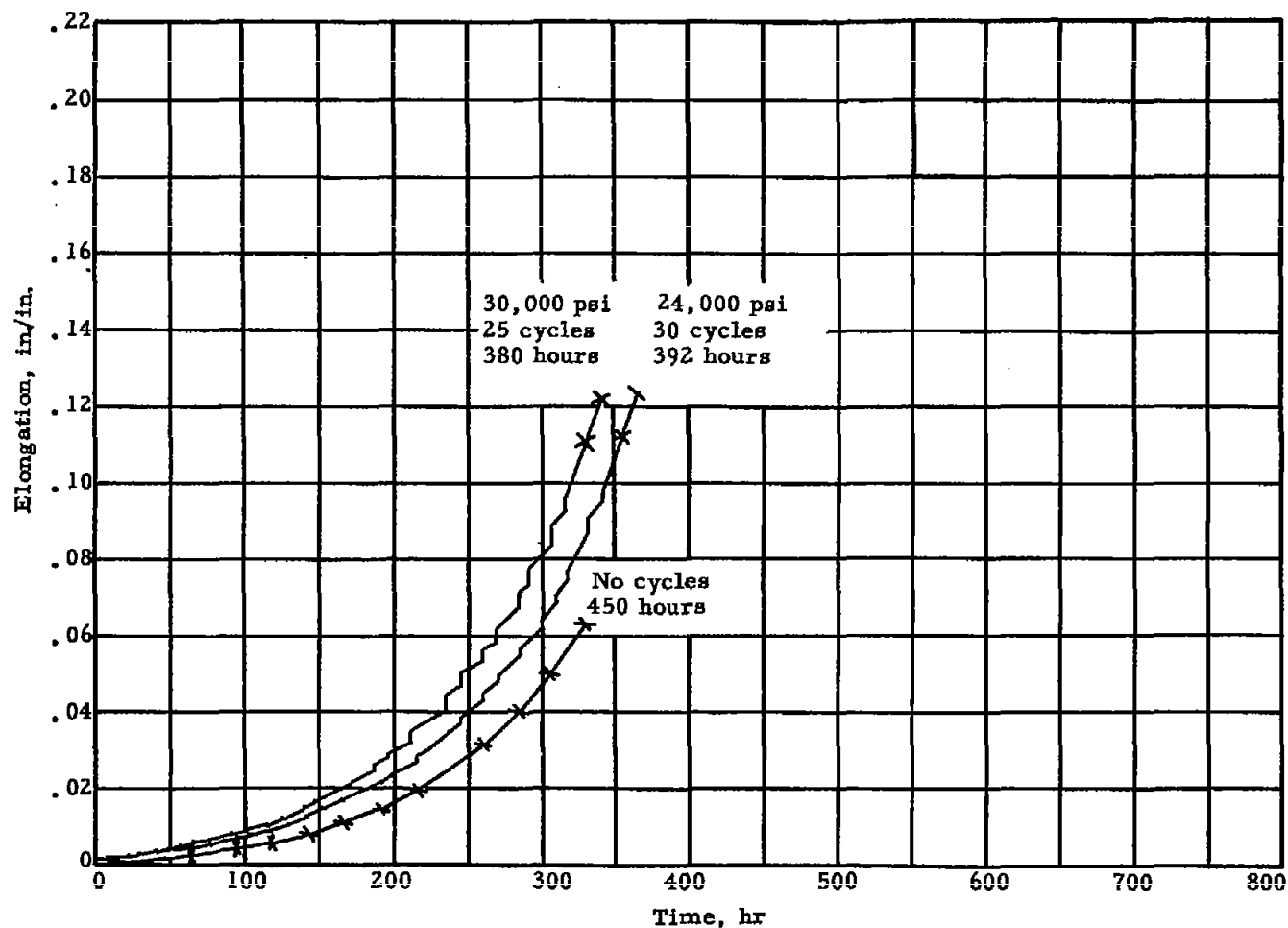
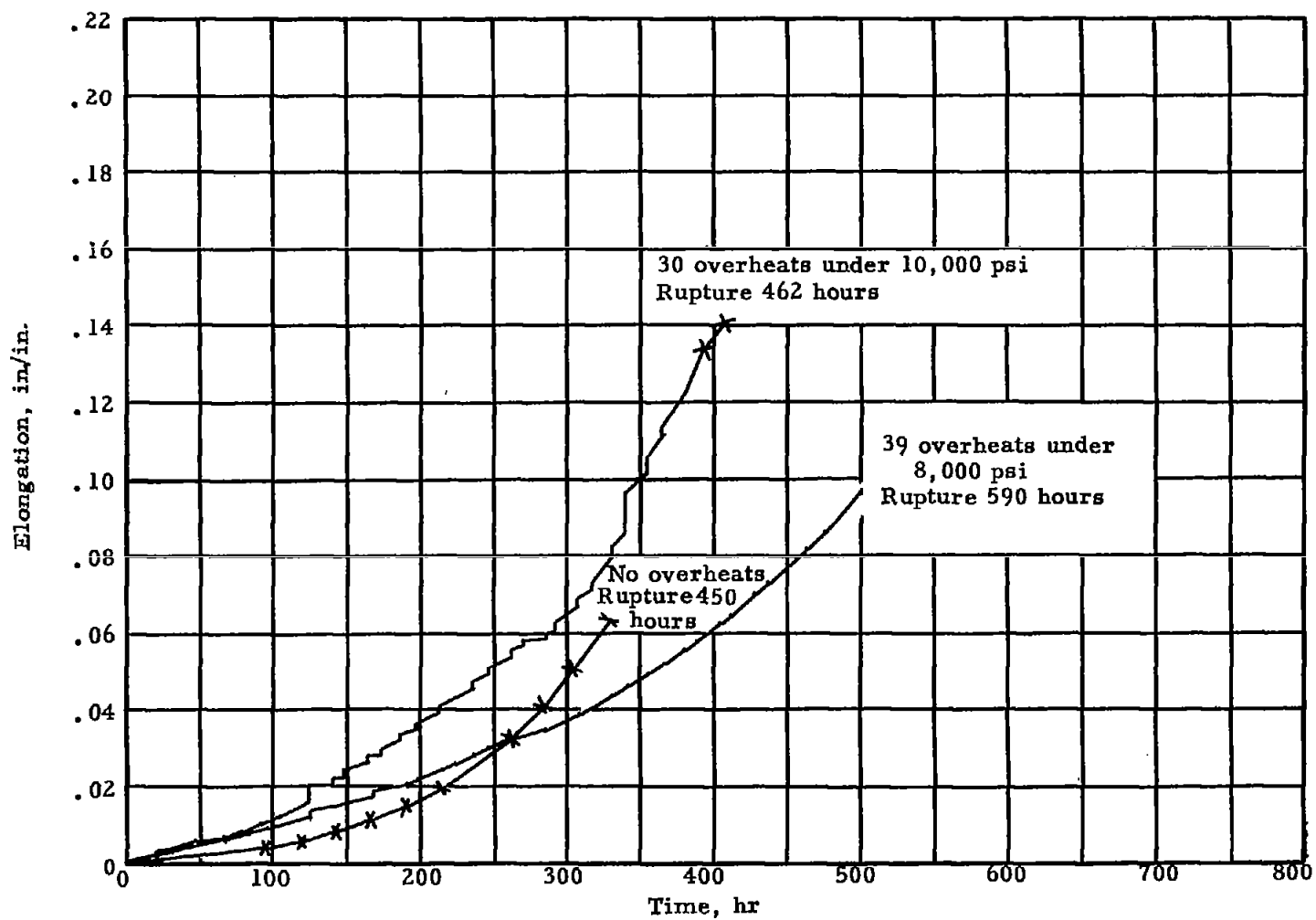


Figure 14.- Hardness of test specimens after fracture as a function of temperature of rupture-testing, preheating, or cyclic overheating as noted.



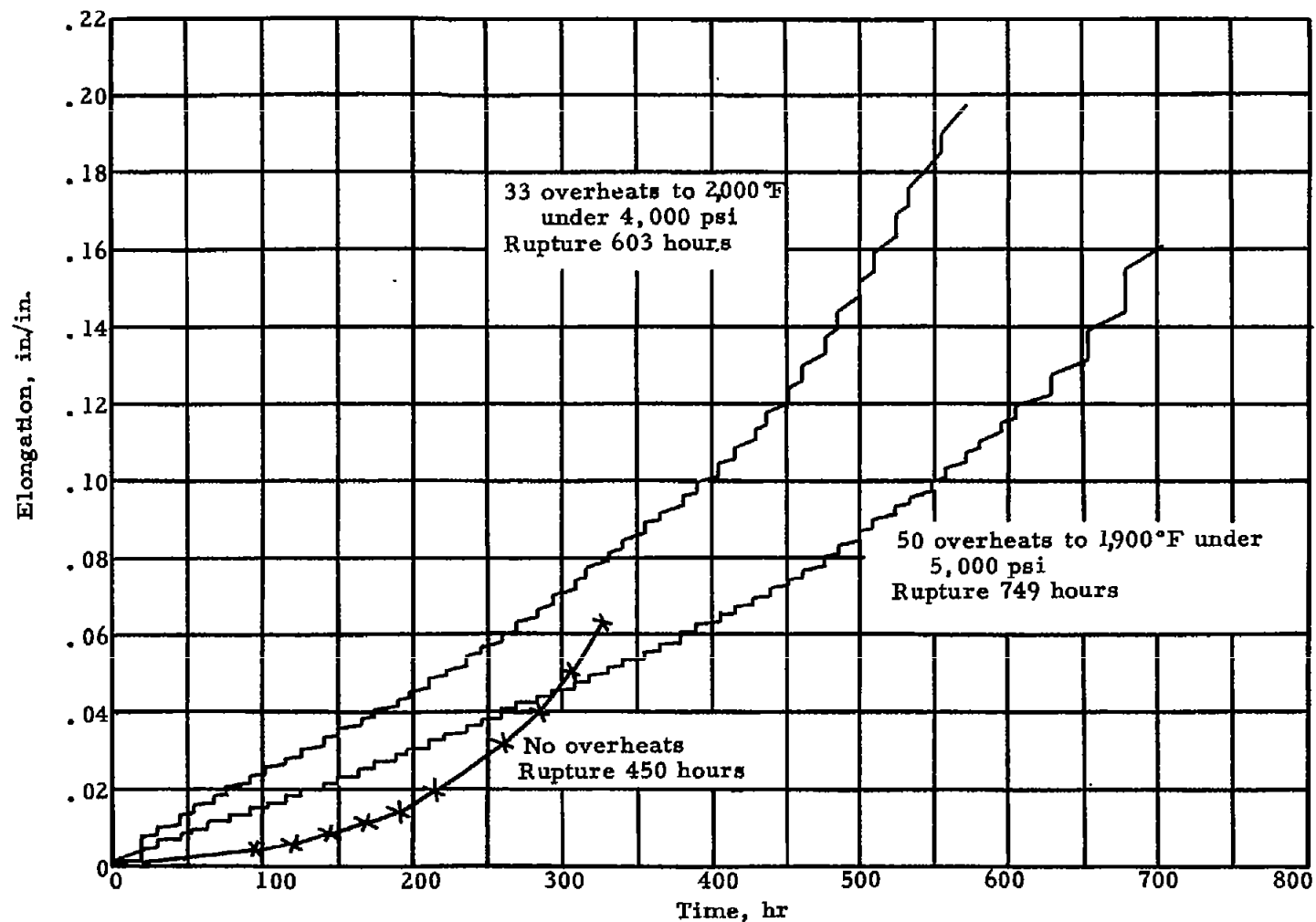
(a) Overheat temperature, 1,650° F.

Figure 15.- Comparative creep curves at 1,500° F and 24,000 psi for tests on specimens overheated to various temperatures for 2 minutes every 12 hours under indicated stress. Numbers indicate overheat stress, rupture time, and number of cycles.



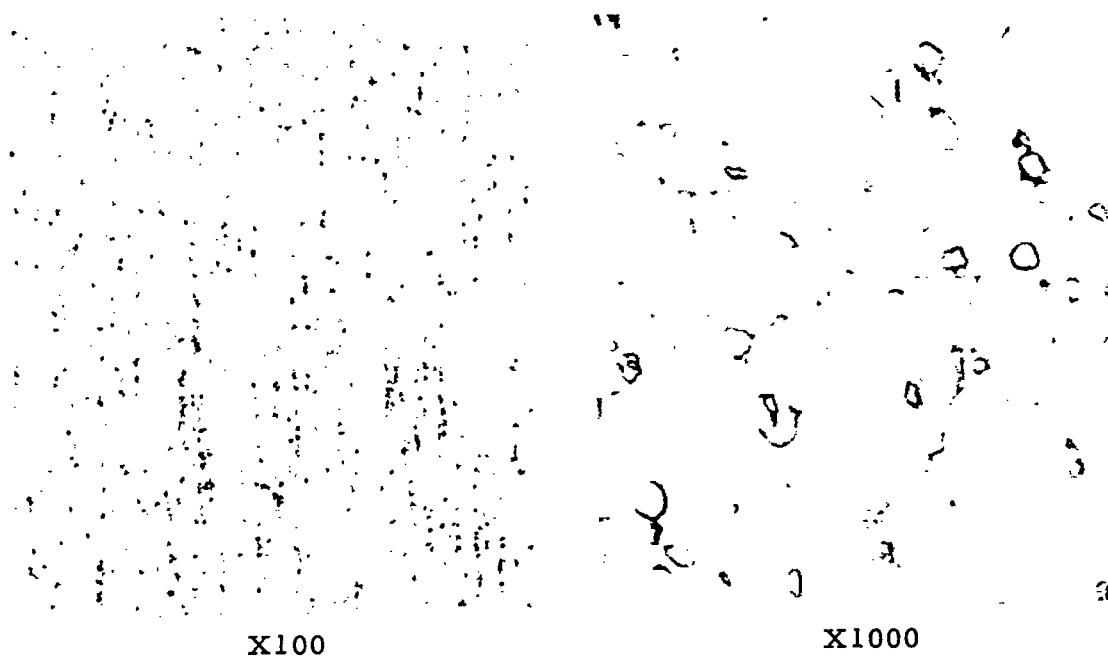
(b) Overheat temperature, 1,800° F.

Figure 15.- Continued.

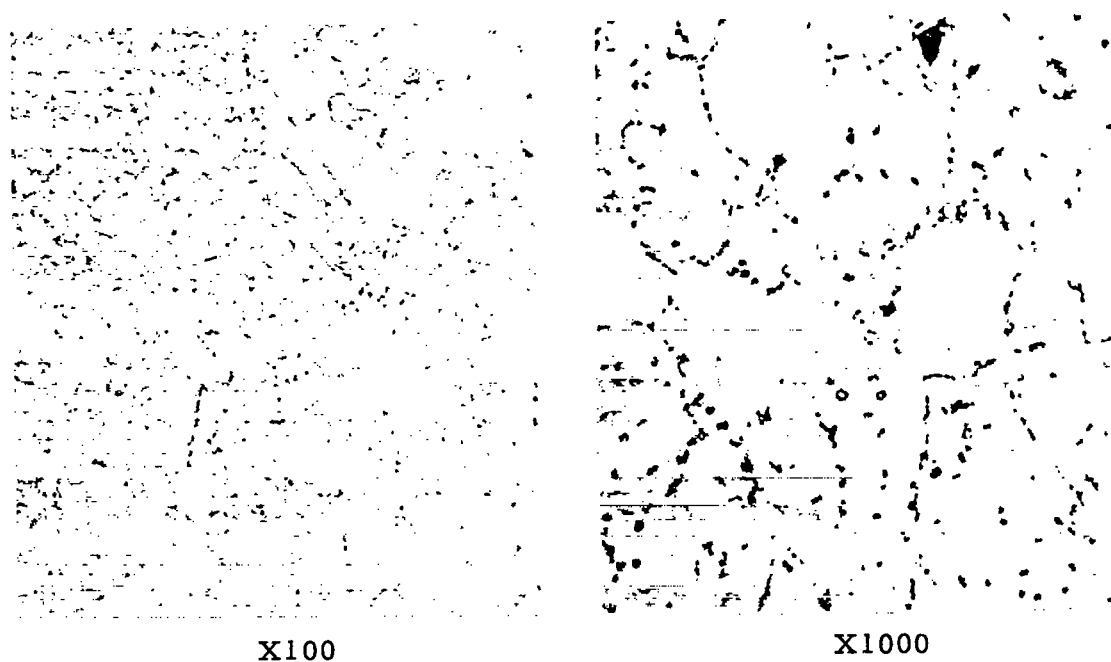


(c) Overheat temperatures as indicated.

Figure 15.- Concluded.

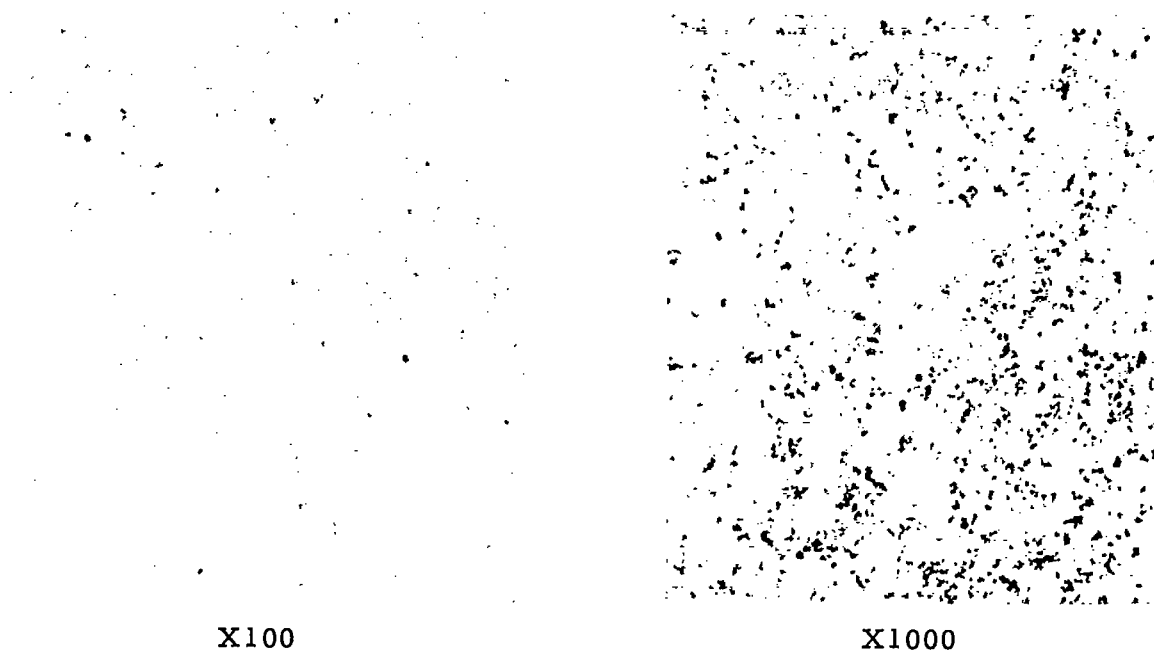


(a) As heat-treated.

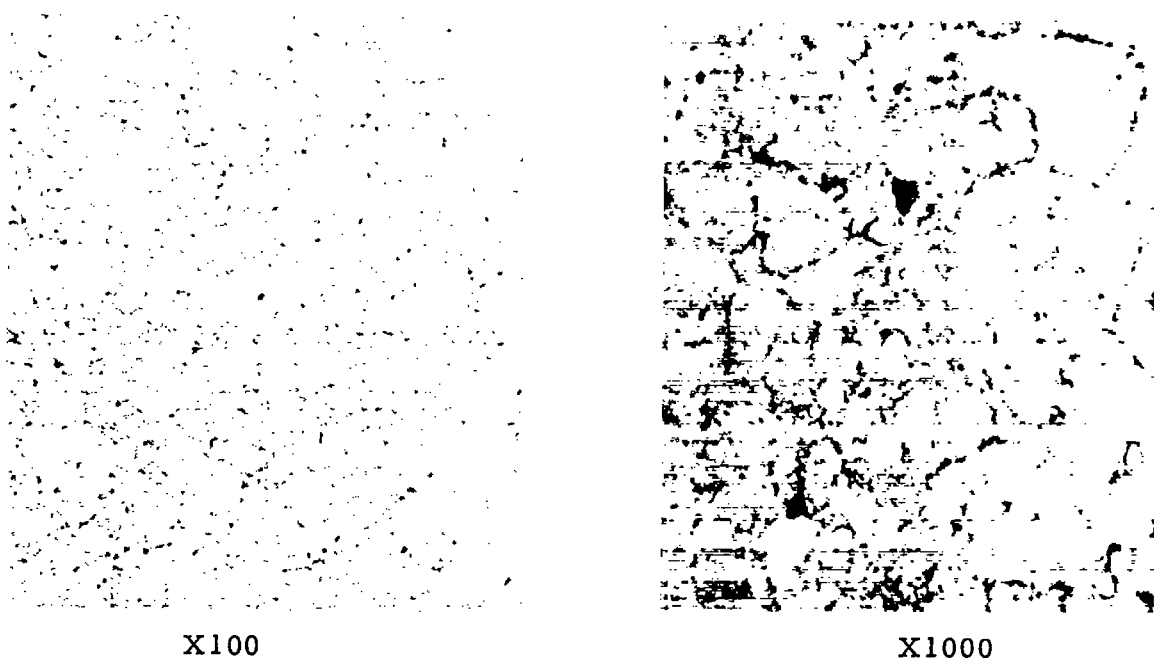


(b) Rupture-tested at 1,500° F under 24,000 psi. Rupture time, 574 hours.

Figure 16.- Microstructure of heat HT-28 after heat treatment and after rupture-testing at 1,500° F.

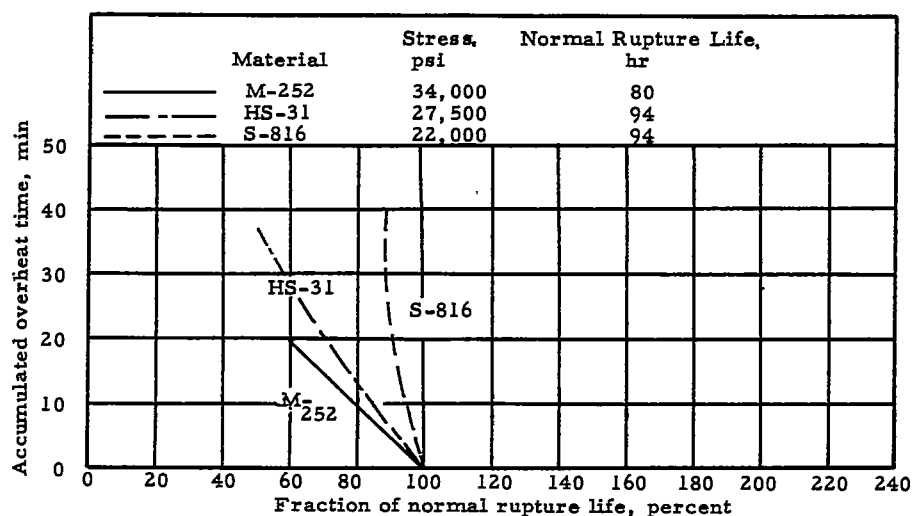


(a) 42 overheats to 1,800° F. Rupture time, 549 hours.

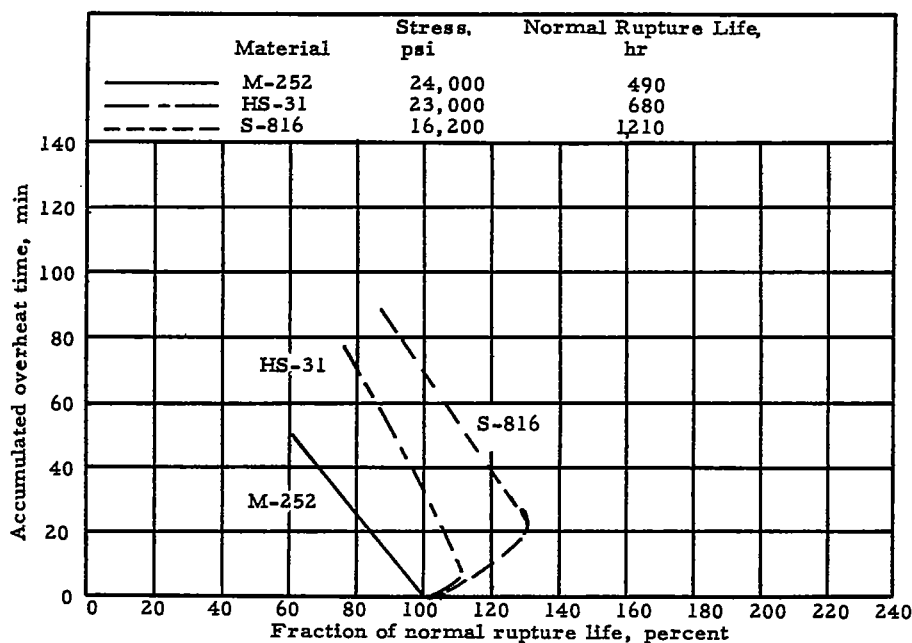


(b) 60 overheats to 2,000° F. Rupture time, 927 hours.

Figure 17.- Effect of continued cyclic overheating on microstructure of specimens tested at 1,500° F and 24,000 psi. Stress removed during 2-minute overhear cycles every 12 hours.

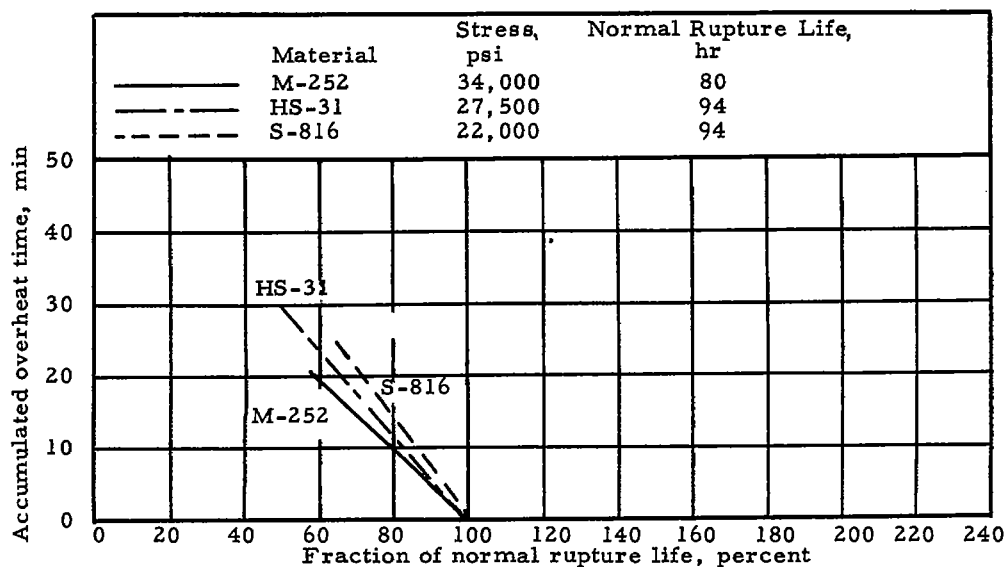


(a) Overheats to 1,650° F every 5 hours.

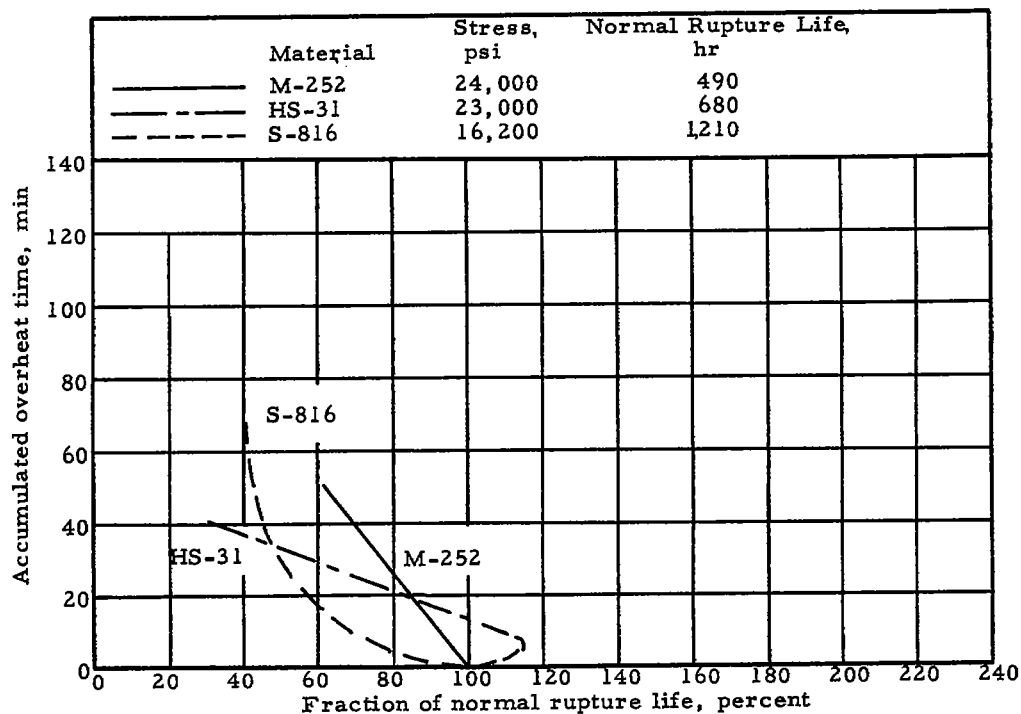


(b) Overheats to 1,650° F every 12 hours.

Figure 18.- Comparison for M-252, HS-31, and S-816 alloys of effect of amount of overheating on rupture life at 1,500° F under indicated stress. Specimens overheated 2 minutes to various temperatures in absence of stress every 5 or 12 hours.

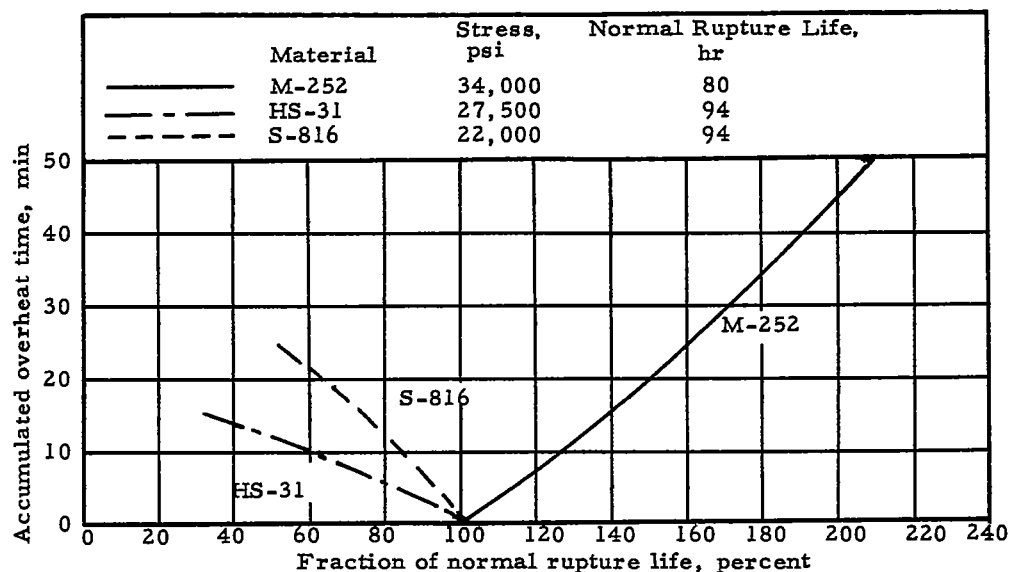


(c) Overheats to 1,800° F every 5 hours.

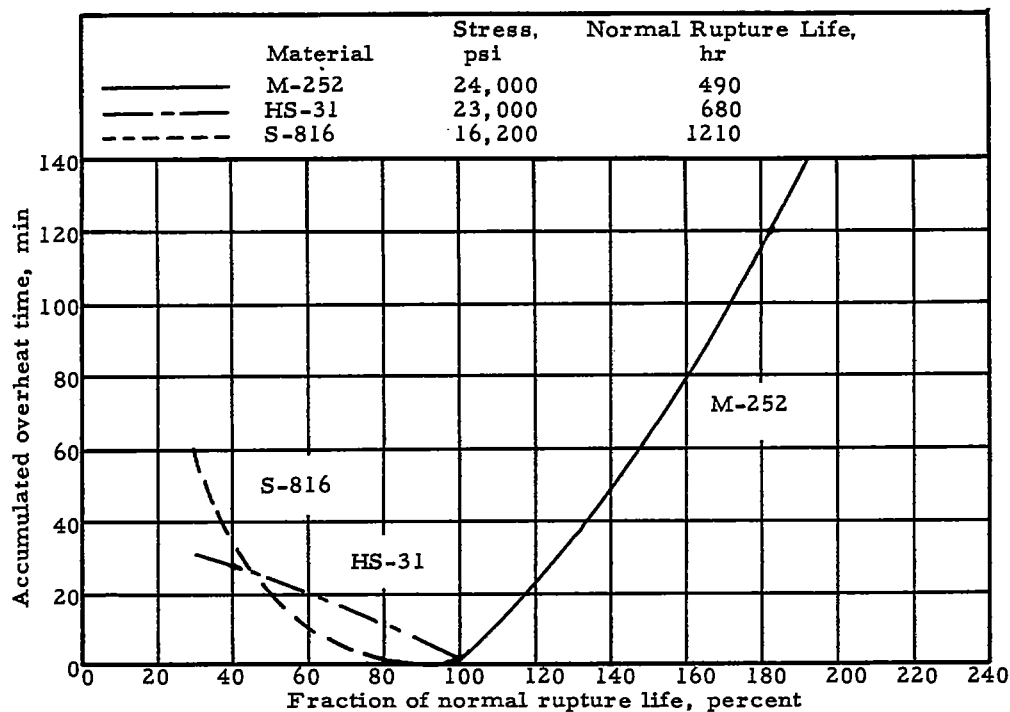


(d) Overheats to 1,800° F every 12 hours.

Figure 18.- Continued.

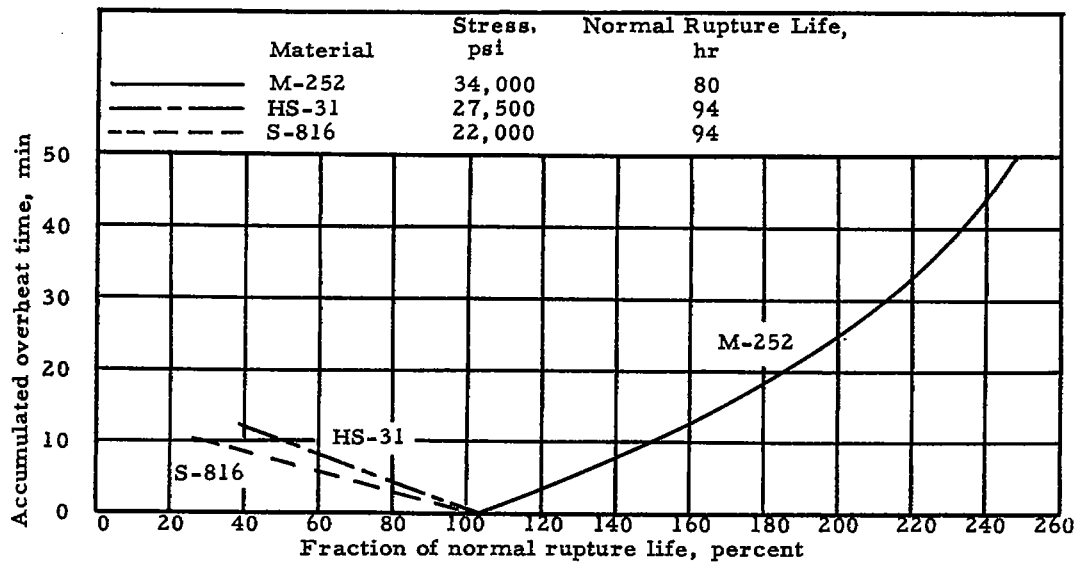


(e) Overheats to 1,900° F every 5 hours.

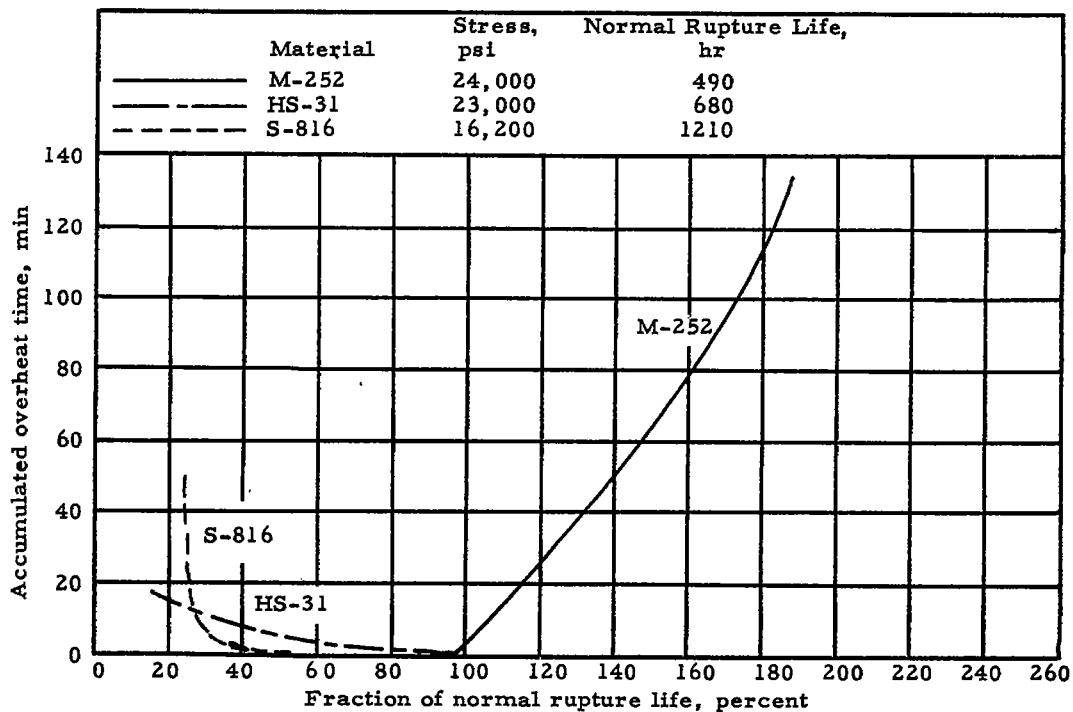


(f) Overheats to 1,900° F every 12 hours.

Figure 18.- Continued.

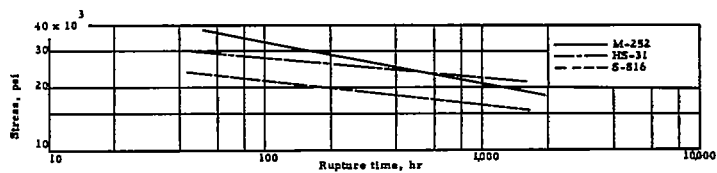


(g) Overheats to 2,000° F every 5 hours.

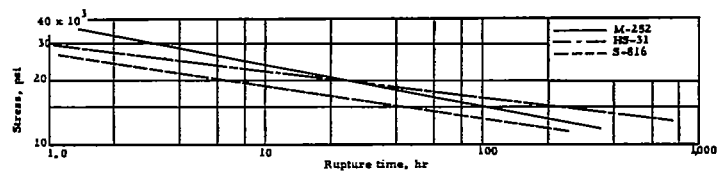


(h) Overheats to 2,000° F every 12 hours.

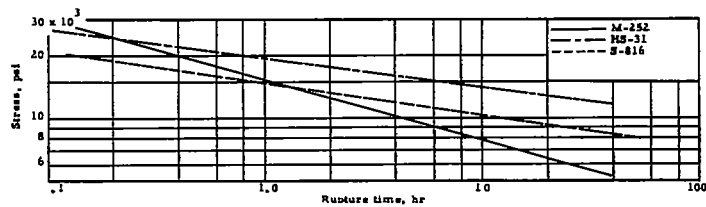
Figure 18.- Concluded.



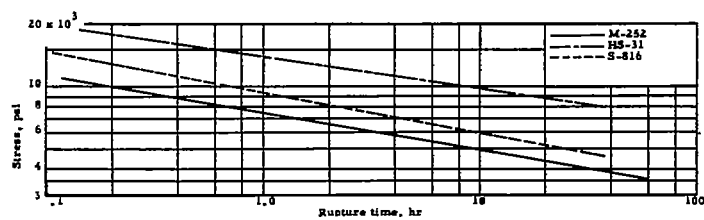
(a) 1,500° F.



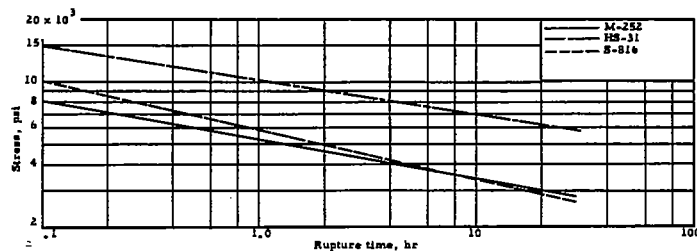
(b) 1,650° F.



(c) 1,800° F.

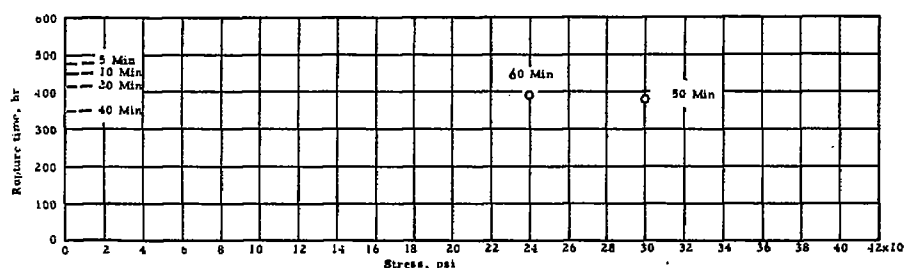


(d) 1,900° F.

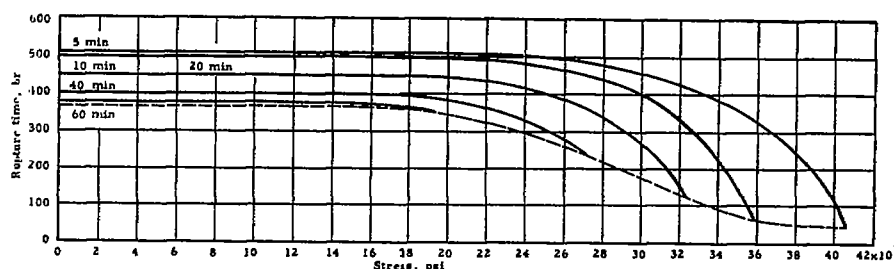


(e) 2,000° F.

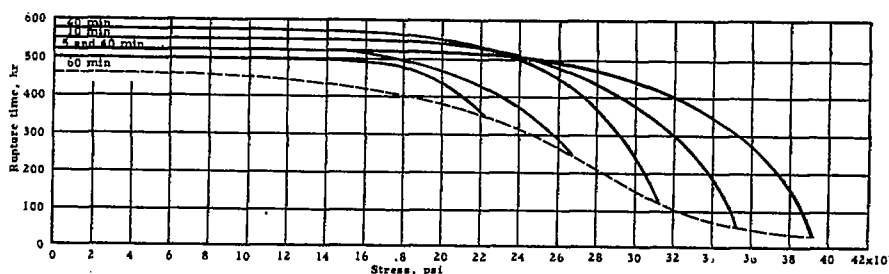
Figure 19.- Curves of stress against rupture time for M-252, HS-31, and S-816 alloys tested at various temperatures used for overheating.



(a) Overheats to $1,650^{\circ}\text{F}$ for M-252 alloy. Stress at $1,500^{\circ}\text{F}$, 24,000 psi.

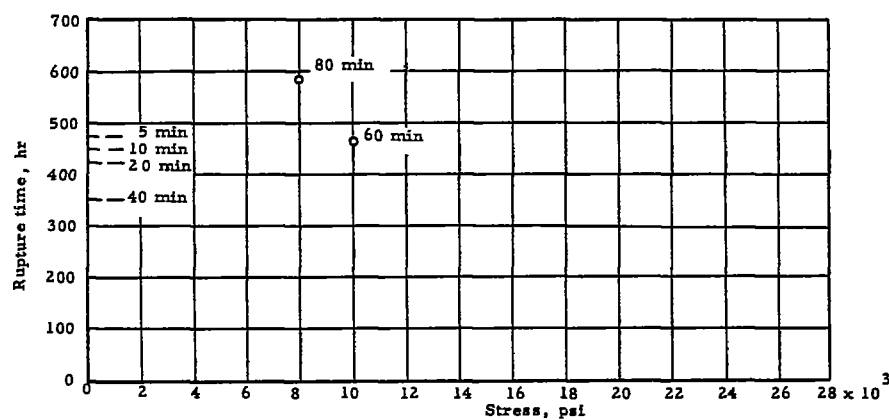


(b) Overheats to $1,650^{\circ}\text{F}$ for HS-31 alloy. Stress at $1,500^{\circ}\text{F}$, 24,000 psi.

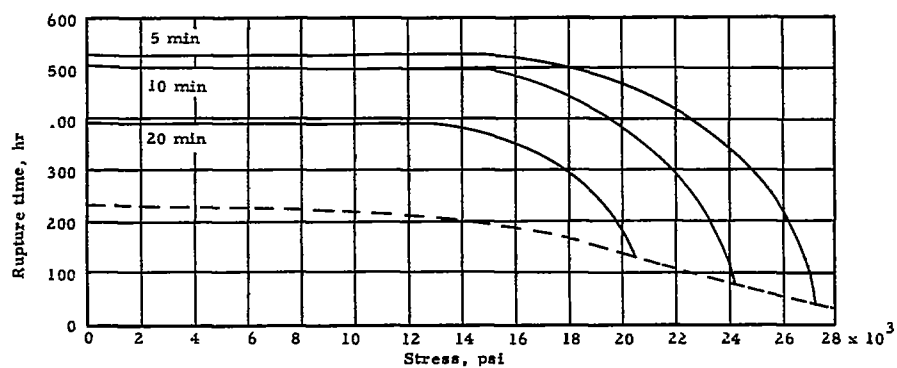


(c) Overheats to $1,650^{\circ}\text{F}$ for S-816 alloy. Stress at $1,500^{\circ}\text{F}$, 18,000 psi.

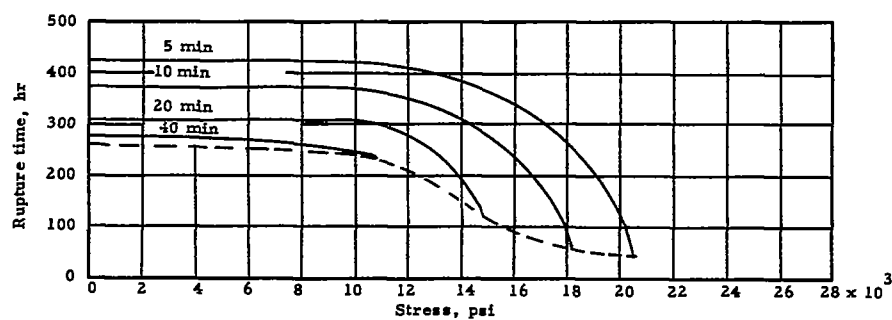
Figure 20.- Effect of stress level present during periodic overheating to various temperatures for indicated total accumulated times of overheating on rupture time for M-252, HS-31, and S-816 alloys at $1,500^{\circ}\text{F}$. Curves of different times of overheating compared for single alloy. Curves calculated for overheats every 12 hours from principle described in text on basis of a rupture time of 500 hours in a normal $1,500^{\circ}\text{F}$ rupture test. Dashed line in each figure represents minimum rupture time possible to accrue indicated total overheat time using fixed cycle frequency above.



(d) Overheats to 1,800° F for M-252 alloy. Stress at 1,500° F, 24,000 psi.

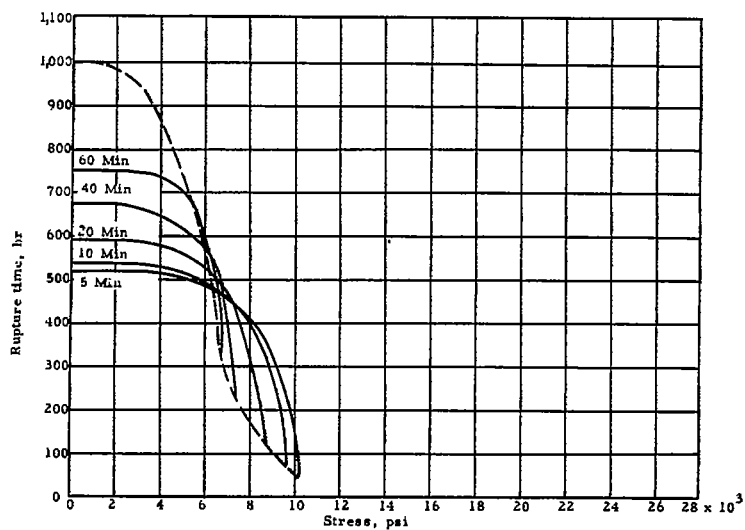


(e) Overheats to 1,800° F for HS-31 alloy. Stress at 1,500° F, 24,000 psi.

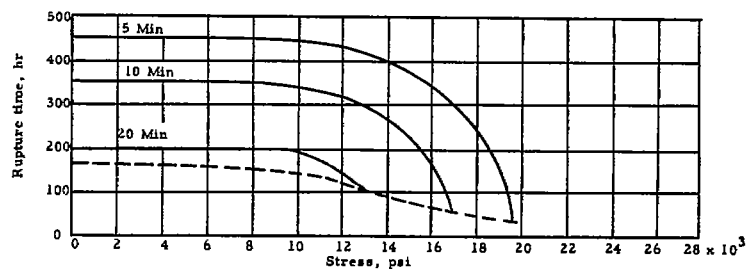


(f) Overheats to 1,800° F for S-816 alloy. Stress at 1,500° F, 18,000 psi.

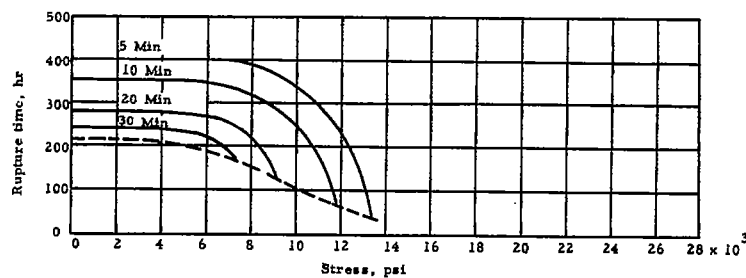
Figure 20.- Continued.



(g) Overheats to 1,900° F for M-252 alloy. Stress at 1,500° F, 24,000 psi.

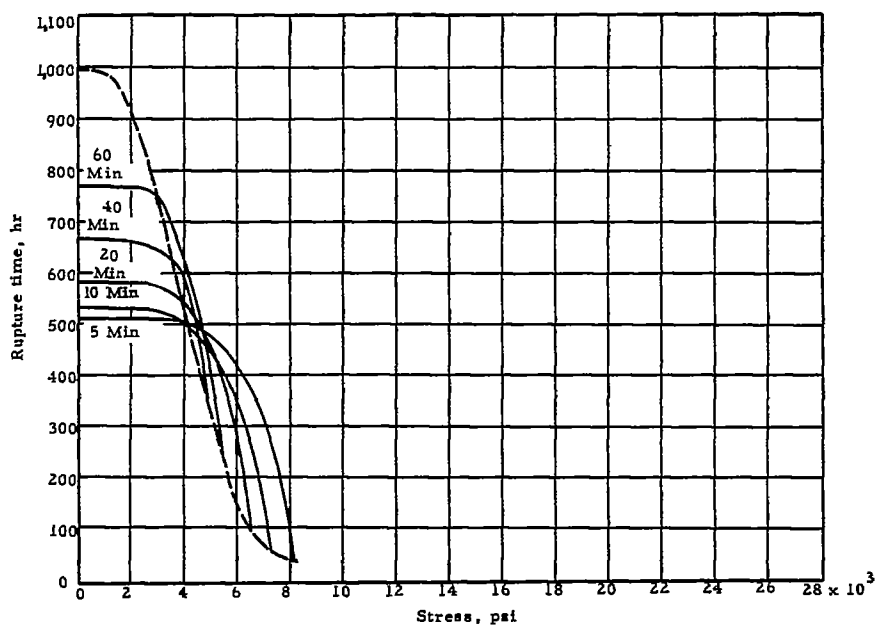


(h) Overheats to 1,900° F for HS-31 alloy. Stress at 1,500° F, 24,000 psi.

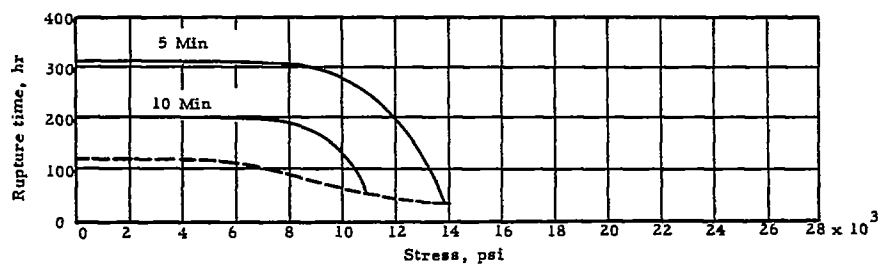


(i) Overheats to 1,900° F for S-816 alloy. Stress at 1,500° F, 18,000 psi.

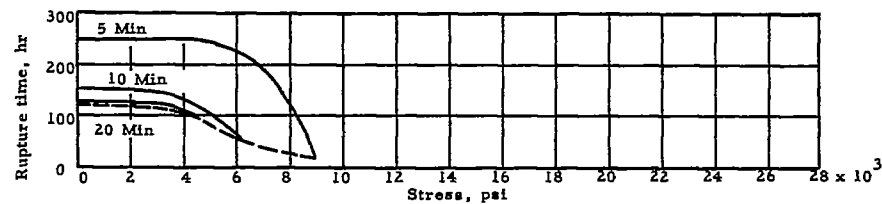
Figure 20.- Continued.



(j) Overheats to 2,000° F for M-252 alloy. Stress at 1,500° F, 24,000 psi.

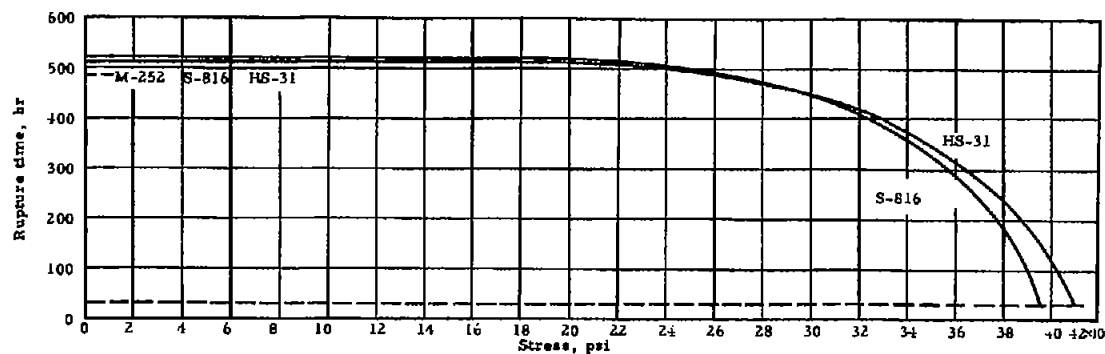


(k) Overheats to 2,000° F for HS-31 alloy. Stress at 1,500° F, 24,000 psi.

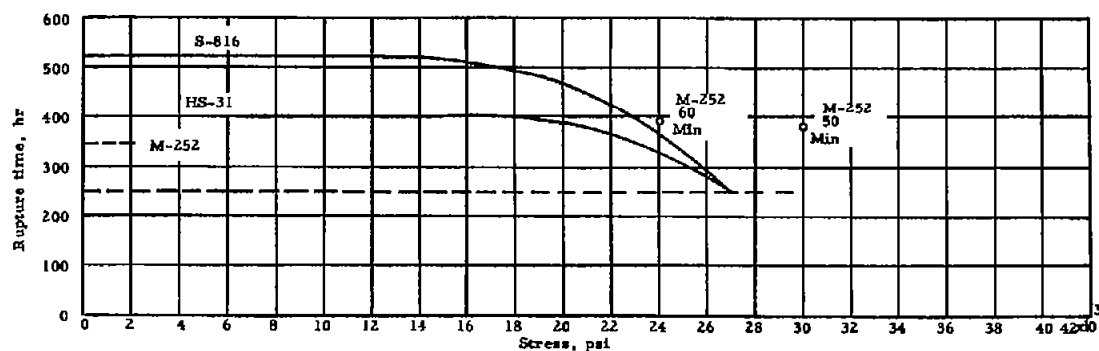


(l) Overheats to 2,000° F for S-816 alloy. Stress at 1,500° F, 18,000 psi.

Figure 20.- Concluded.

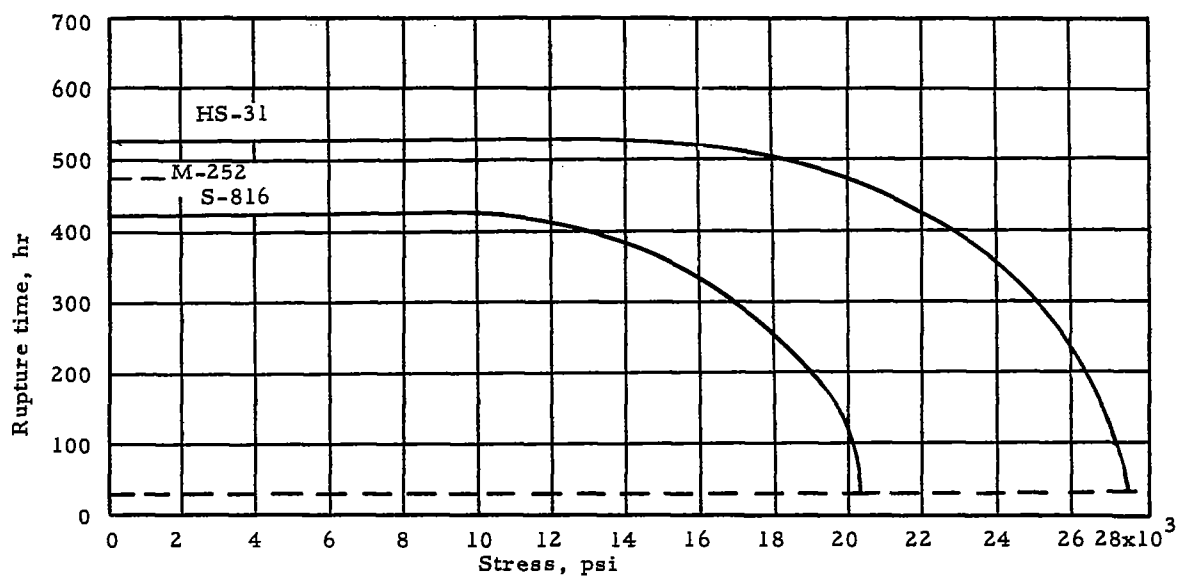


(a) Overheats to $1,650^{\circ}$ F for 5 minutes of overheating.

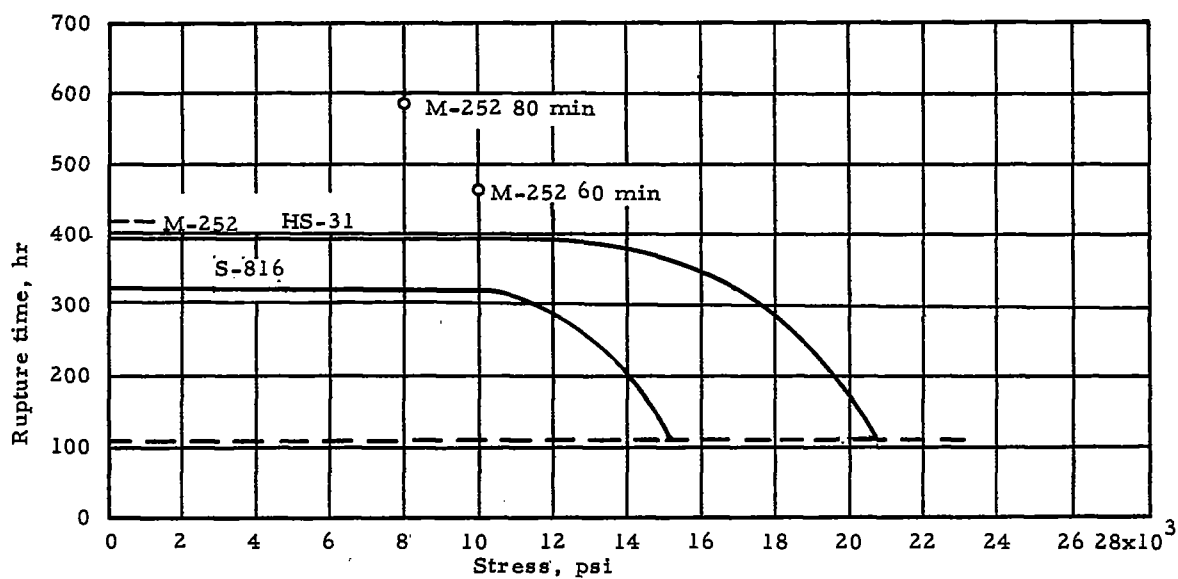


(b) Overheats to $1,650^{\circ}$ F for 40 minutes of overheating.

Figure 21.- Comparison of effect of stress level present during periodic overheating to various temperatures for indicated total accumulated times of overheating on the rupture time for M-252, HS-31, and S-816 alloys at $1,500^{\circ}$ F. Curves for different alloys compared for one time of overheating. Curves calculated for overheats every 12 hours from principle described in text on basis of a rupture time of 500 hours in a normal $1,500^{\circ}$ F rupture test. Dashed line in each figure represents minimum rupture time possible to accrue indicated total over-heat time using fixed cycle frequency above.

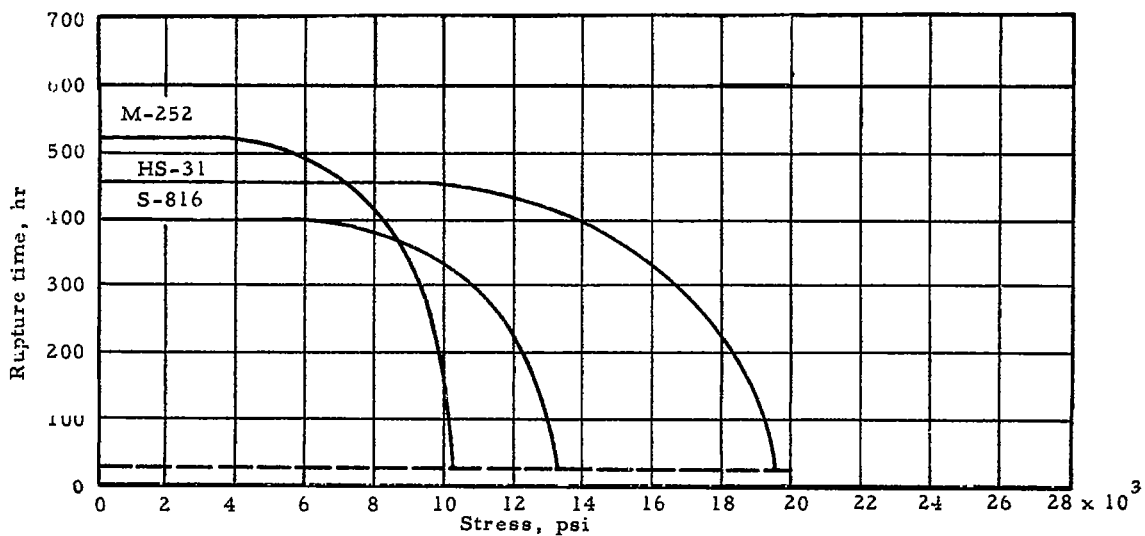


(c) Overheats to 1,800° F for 5 minutes of overheating.

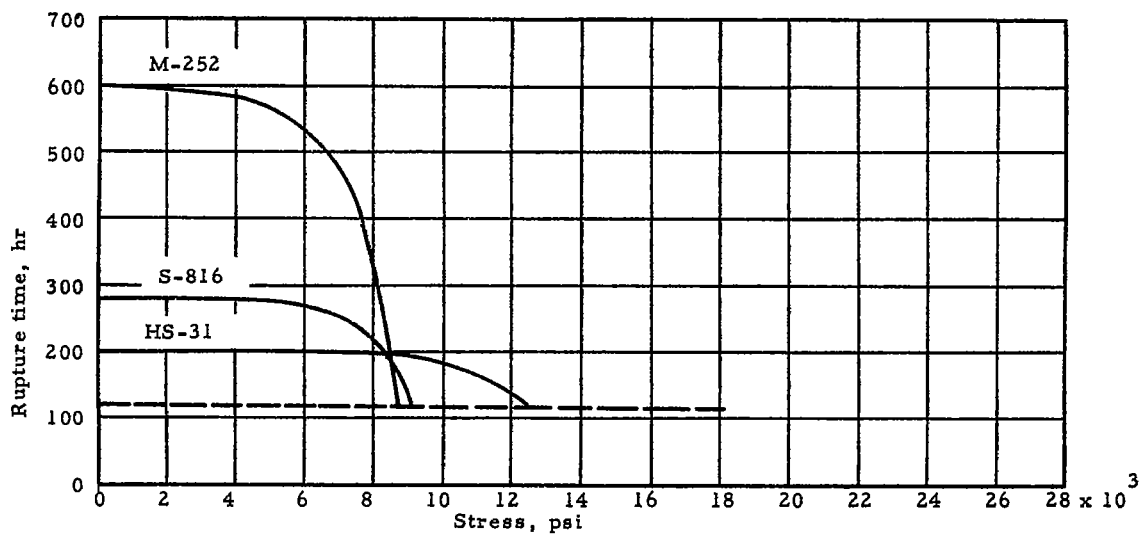


(d) Overheats to 1,800° F for 20 minutes of overheating.

Figure 21.- Continued.

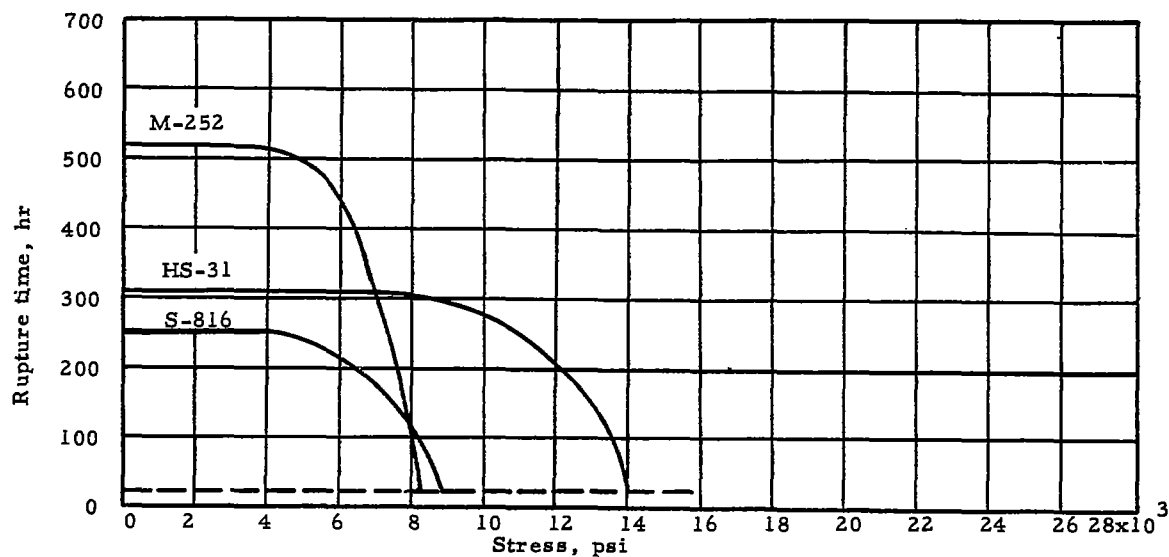


(e) Overheats to 1,900° F for 5 minutes of overheating.

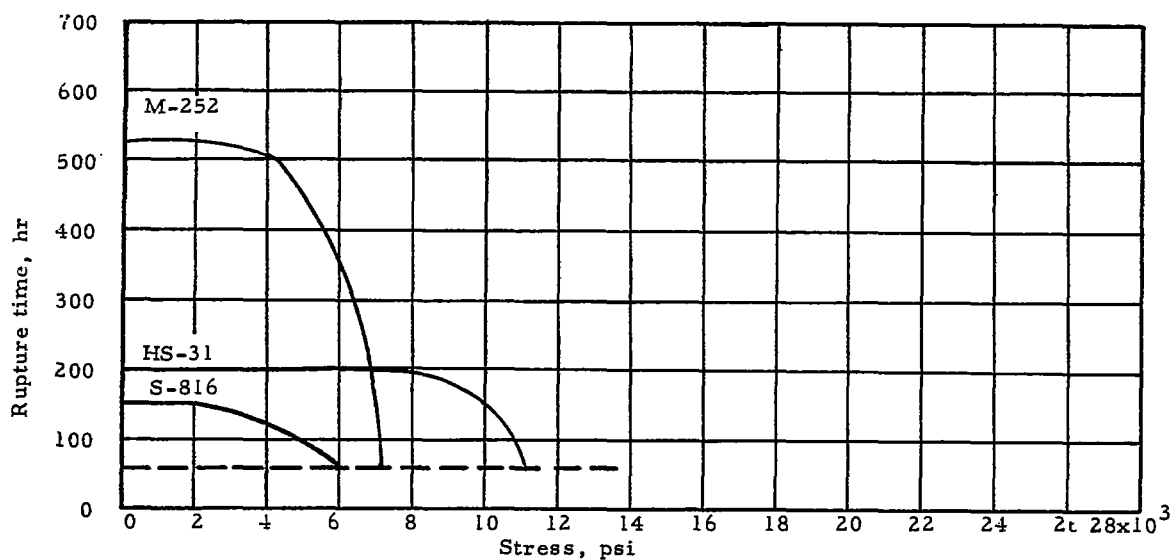


(f) Overheats to 1,900° F for 20 minutes of overheating.

Figure 21.- Continued.



(g) Overheats to 2,000° F for 5 minutes of overheating.



(h) Overheats to 2,000° F for 10 minutes of overheating.

Figure 21.- Concluded.